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MUCK UTILIZATION IN THE URBAN TRANSPORTATION TUNNELING PROCESS

T.K. Liu
D.G. Gifford
R.P. Stulgis
D.L. Freed

HALEY & ALDRICH, INC.
238 Main Street
Cambridge MA 02138

DECEMBER 1977
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16. Abstract

This report provides transportation system planners and designers with the necessary information to use more efficiently the earth and rock materials produced during excavation for transportation tunnels and large excavations. The excavated materials, or "tunnel muck," have been traditionally treated as a waste product of the construction process. This report investigates potential uses of tunnel muck, and documents the necessary technical and planning procedures which may be used to evaluate its utilization.

Six guideline steps for muck utilization planning are presented. Selection of a Muck Utilization Coordinating Committee (MUCC) for implementing the guideline steps is described. It is intended that the MUCC prepare contract documents as part of the bid package for the tunnel project.

The muck utilization planning concepts have been investigated for three metropolitan areas in the United States which are actively planning rapid transit systems. A trial case study of the muck utilization guidelines is described for the Baltimore Rapid Transit System.

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PREFACE

This report presents the results of a detailed investigation into the potential for muck utilization in the urban transportation tunneling process. Primary investigation was completed by Haley & Aldrich, Inc., Consulting Geotechnical Engineers and Geologists, with the assistance of Jenny Engineering Corporation.

The work was completed under Contract DOT-TSC-836 for the Transportation Systems Center (TSC), on behalf of the office of Rail Technology, of the Urban Mass Transportation Administration (UMTA), Office of Technology Development and Deployment, U.S. Department of Transportation (DOT). The guidance and support throughout this study of Gilbert Butler, of UMTA, and Gerald Saulnier, Technical Monitor for TSC, have been greatly appreciated.

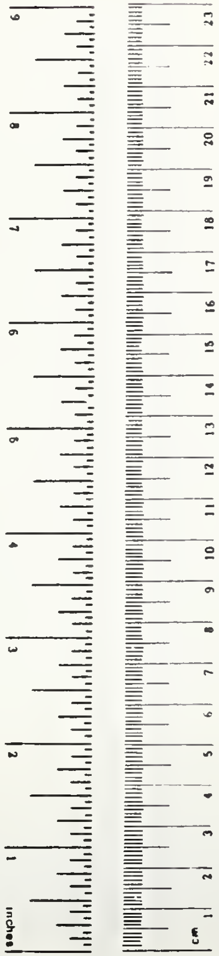
The cooperation and assistance of those organizations, including government and transit agencies, engineers and contractors who contributed valuable information in response to our review of current muck disposal and utilization practice are gratefully acknowledged. A complete list of respondents to a questionnaire and to an evaluation of the muck utilization handbook are presented in Appendix A and Table 9-1 respectively.

The authors wish to acknowledge the assistance of Kenneth Recker and Gary Brierley of Haley & Aldrich, Inc. and Robert Jenny of Jenny Engineering Corporation for their contributions to various sections of the report.

METRIC CONVERSION FACTORS

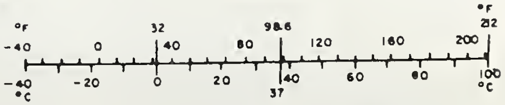
Approximate Conversions to Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
in	inches	2.5	centimeters	cm
ft	feet	30	centimeters	cm
yd	yards	0.9	meters	m
mi	miles	1.6	kilometers	km
		AREA		
in^2	square inches	6.5	square centimeters	cm^2
ft^2	square feet	0.09	square meters	m^2
yd^2	square yards	0.8	square meters	m^2
mi^2	square miles	2.6	square kilometers	km^2
	acres	0.4	hectares	ha
		MASS (weight)		
oz	ounces	28	grams	g
lb	pounds	0.45	kilograms	kg
	short tons (2000 lb)	0.9	tonnes	t
		VOLUME		
tsp	teaspoons	5	milliliters	ml
Tbsp	tablespoons	15	milliliters	ml
fl oz	fluid ounces	30	milliliters	ml
c	cups	0.24	liters	l
pt	pints	0.47	liters	l
qt	quarts	0.95	liters	l
gal	gallons	3.8	liters	l
ft^3	cubic feet	0.03	cubic meters	m^3
yd^3	cubic yards	0.76	cubic meters	m^3
		TEMPERATURE (exact)		
°F	Fahrenheit temperature	5/9 (after subtracting 32)	Celsius temperature	°C



Approximate Conversions from Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
mm	millimeters	0.04	inches	in
cm	centimeters	0.4	inches	in
m	meters	3.3	feet	ft
m	meters	1.1	yards	yd
km	kilometers	0.6	miles	mi
		AREA		
cm^2	square centimeters	0.16	square inches	in^2
m^2	square meters	1.2	square yards	yd^2
km^2	square kilometers	0.4	square miles	mi^2
ha	hectares (10,000 m^2)	2.5	acres	
		MASS (weight)		
g	grams	0.035	ounces	oz
kg	kilograms	2.2	pounds	lb
t	tonnes (1000 kg)	1.1	short tons	
		VOLUME		
ml	milliliters	0.03	fluid ounces	fl oz
l	liters	2.1	pints	pt
l	liters	1.06	quarts	qt
l	liters	0.26	gallons	gal
m^3	cubic meters	35	cubic feet	ft^3
m^3	cubic meters	1.3	cubic yards	yd^3
		TEMPERATURE (exact)		
°C	Celsius temperature	9/5 (then add 32)	Fahrenheit temperature	°F



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1. INTRODUCTION

1.1 PURPOSE

The utilization of excavated materials (muck) from tunnels can produce both economic and environmental benefits. Economically, the owner profits by reusing "waste" materials. Environmentally, unsatisfactory disposal practices are eliminated and marginal land areas can be transformed into desirable locations for recreation, housing, industry, and wildlife preserves. The purpose of this study is to develop a workable approach to muck utilization for transit tunnels, including cut and cover construction, in the urban area.

It is intended that muck utilization planning would be included in the overall planning effort necessary for a transit system development.

1.2 SYNOPSIS

The following is a brief synopsis of this investigation:

a. Traditional Practice of Muck Utilization. Sources for review of current practice included literature, personal interviews, and written surveys to firms and individuals. Three case histories were selected for in-depth study of current muck utilization practice.

b. Methods of Tunnel Construction. A comprehensive review of tunnel construction methods was undertaken in order to clearly define the methods of muck production. Only those techniques affecting the evaluation of muck characteristics were investigated. Future construction procedures were studied for an indication of how the character of muck might change with developments in tunnel excavation.

c. Program of Subsurface Exploration. The current methods of subsurface exploration and testing were reviewed from the perspective of muck utilization planning. The need for additional field and laboratory testing was also evaluated.

d. Potential Uses of Tunnel Muck. A thorough review of the potential uses of tunnel muck, from landfill to concrete aggregate, brick manufacturing and industrial raw materials was undertaken. Those uses which showed promise as technical and economical solutions to the problem of muck disposal were investigated in greater detail. Methods for improving the engineering properties of tunnel muck were also investigated.

e. Contingency Assessment. An evaluation of contingencies relative to muck utilization revolved around three areas of concern: subsurface conditions, methods of construction, and plans for utilization.

f. Muck Utilization Guidelines. A list of six guideline steps was prepared for muck utilization.

g. Muck Utilization Coordinating Committee. An implementation program was recommended for muck utilization. The program involves selecting an acting committee to evaluate current and planned material requirements, determining of one or more muck utilization schemes, planning for their implementation, and preparing contract documents.

h. Handbook. A concise summary of the muck utilization planning concepts was written in a handbook format (the handbook is available). A draft of the handbook was distributed for comment to various transit authority personnel throughout the United States. Their comments, as discussed herein, were evaluated and incorporated into the handbook.

i. Case Study. The muck utilization planning concepts were investigated for three metropolitan areas in the United States actively planning rapid transit systems. Additionally, a trial case study of the muck utilization guidelines was made for the Baltimore Region Rapid Transit System - Phase I, Section A. As a result of the trial case study, a muck utilization plan was written and incorporated into the project contract documents.

1.3 TUNNEL MUCK - WHAT IS IT?

Tunnel muck consists of all materials removed from a tunnel during the construction process. It includes soil or rock materials, excess water, and construction debris. The soil or rock material forms the largest percentage of the muck and can vary from soft clay or inorganic silt to the hardest of granite. Rain, water from construction equipment, or groundwater seepage from completed protions of the tunnel, all contribute to excess water accumulating in the muck. Debris includes all types of discarded equipment and materials used for construction, such as concrete, wood, and steel.

The debris in tunnel muck usually comprises a very small percentage of the total volume. There are several sources for this debris including in-situ fill, construction materials and miscellaneous sources. A thick layer of fill is very common in urban areas due to previous demolition or construction activities. This fill may form a significant protion of the muck, especially in the early stages of a cut and cover project. Construction materials accumulate in the muck on a continuous basis as construction proceeds. Even small amounts of debris can result in problems with muck utilization because it represents a deleterious substance in an otherwise natural material.

In addition to the in-situ materials through which the tunnel is excavated, the muck characteristics depend also on the particular excavation methods employed. Tunnel construction is usually divided into soft ground or hard ground classifications.

Tunneling through soft ground gravels, sands, silts, and clays is usually accomplished using shields which may or may not be equipped with mechanical excavating equipment. Mining can also be accomplished by manpower, using jackhammers, clay knives, and shovels. Soft ground tunneling methods remold soil and drastically change its strength, compressibility, and permeability characteristics from its undisturbed in-situ state. These methods do not normally alter grain size, surface texture, or chemical properties.

Tunneling through hard ground (rock) can be done by either conventional drill and blast methods or by the newly developed tunnel boring machine (TBM). Rock fragmentation of drill and blast muck depends largely on drill hole characteristics, amount and type of explosive, blasting pattern, overall geometry, and rock mass characteristics. Typically, the drill and blast muck ranges in size from 2 ft to fine sand materials and the particles are generally very angular. TBM's produce much smaller sized material and particles which are typically flat and elongated. Maximum dimensions typically range from 3 to 5 in. long by 2 in. wide and 1/2 to 1 in. thick. Particle sizes are more frequently within the range of fine sand and sometimes clay. Water is commonly used at the tunnel face for dust control measures; the uses of detergents and rock softening chemicals are currently being investigated.

2. TRADITIONAL PRACTICE OF MUCK UTILIZATION

2.1 INTRODUCTION

Haley & Aldrich, Inc. investigated current practice and case studies related to muck utilization in the urban rapid transit tunneling process. This section summarizes information obtained from a literature search of civil engineering, tunneling and construction journals; from a survey of tunnel contractors, engineers and owners; and through interviews and written correspondence with people in the tunneling and materials processing industries.

2.2 MUCK UTILIZATION - HISTORICAL PERSPECTIVE

Great controversies and debates surrounded the early tunneling ventures. The following quote, for example, is taken from a speech delivered by Derby, a proponent of the Hoosac Tunnel and a decided opponent of a tunnel beneath the Hudson River. The speech was delivered at a special hearing convened in 1853 by the Massachusetts Legislature to determine the worthiness of each project and thereby assign funds [2-1].*

> "And allow me to ask, What is to be done with the water while this tunnel is driven fourteen hundred feet under the oozy bed of the Hudson? Will there not be some percolation here, Mr. Chairman? We are told, Sir, that the water will occasion no difficulty; but did it cause none in the tunnel under the Thames, that gigantic folly of England, which has cost some four millions of dollars for no useful purpose? The Thames at London Bridge, is but half the width of the Hudson at Albany. But the water is to cause no inconvenience, Mr. Chairman. I am, I confess, somewhat amused with the intense solicitude of Cap. Swift, as to the water we may encounter in tunneling the summit of the Green Mountains, and the composure and equanimity with which he regards the same element when he dives below a noble river, one of the great arteries of Commerce."

Ultimately the Hoosac Tunnel scheme was selected over the Hudson River Tunnel.

The following sections provide a brief outline of two historically significant projects - the Thames Tunnel and the Hoosac Tunnel.

---

*Numbers in brackets [ ] refer to entries in Section 12-References.

2.2.1 Thames River Crossing

During the early 19th century about 3700 passengers were ferried across the Thames River each day. A two-mile detour was required for wagons to reach the opposite shore. As a result of the traffic demands, Richard Treventhick attempted to build the first tunnel under the Thames in 1817. After five years, however, the work was abandoned [2-2].

In 1825, Marc Isambard Brunel proposed a scheme for tunneling under the river, using a cast iron shield modeled after the actions of the teredo, a notorious wood boring worm. Brunel and his son, Isambard Kingdom Brunel, instituted techniques for underground and underwater work which are, in principle, still used today [2-3].

Tunneling commenced in March 1825 from a brick lined shaft which was lowered, caisson style, through the clay foundation soils on the shore of the river. The shaft was 42 ft deep and 50 ft in diameter with 3 ft thick brick lined walls.

According to job records, some of the clay excavated from the shaft was taken to a nearby kiln, fired into bricks, and returned to the site for use in the construction [2-4]. It appears, however, that the volume of acceptable brick making clay encountered in the shafts was not sufficient to supply the entire works, and Brunel opened other local brick works [2-5]. The inventive Brunel must therefore be credited with adopting the earliest known muck utilization scheme for urban tunnels.

Brunel predicted strong blue clay under the river, based on borings taken along the route. The shaft excavation, however, encountered numerous pockets of sand and gravel, an indicator of trouble. The sand and gravel apparently reduced the brick making efforts and also contributed to several floods during the tunneling. The most serious flooding accident claimed the lives of six tunnelers and nearly took the life of Brunel's son.

The Brunels persisted and, despite construction difficulties and financial setbacks, the tunnel was completed and fully lined in 1843. During the first three months of 1843, more than one million visitors walked through the tunnel. In 1865, the tunnel was purchased and converted to a railroad tunnel. Eventually it was incorporated into the London Underground.

2.2.2 Hoosac Tunnel

The Hoosac Tunnel is a great civil engineering accomplishment. Since its construction through the Hoosac Mountains in western Massachusetts between 1851 and 1875, the 4-3/4 mile route has been used as a railroad tunnel. It is currently owned and operated by the Boston & Maine Corporation.

The rock through which the tunnel was excavated was reasonably competent, except for several hundred feet of intensely weathered rock at the west portal. All of the rock is metamorphic, progressing from marble in the west to gneiss and schist in the east. The basic structure of the mountain is an anticline overturned slightly to the west with low dips on the west flank and higher dips to the east. Groundwater seepage into the tunnel during construction was considerable.

Contemporary geologists, most notably Professor Edward Hitchcock, accurately predicted the tunnel geology except for the extremely poor conditions at the west end. However, some of Professor Hitchcock's construction predictions were erroneous. For instance, he predicted that the tunnel would be as stable as a hole drilled through a piece of wood. Eventually, 7600 ft, or 30 percent of the tunnel, had to be lined with a brick arch. The bottom of the tunnel at the west end had to be further supported with an inverted arch (referred to today simply as the invert). Another miscalculation by Professor Hitchcock was his assumption that water could not possibly percolate in "solid" rock to the level of the tunnel.

The original plan was to construct a single track tunnel, 12 ft wide and 14 ft high. With time, however, it was realized that the increase in railroad traffic would sonner or later necessitate a double track tunnel. The expense of enlarging the tunnel under traffic was avoided by increasing its size to approximately 26 ft in diameter during original construction. It was not until the 1920's that the tunnel had to be enlarged again to accomodate larger locomotives and rolling stock.

The Hoosac Tunnel has two shafts: the central shaft, which is 1030 ft deep and 22 by 14 ft in area; and the west shaft, which is 310 ft deep and 10 ft in diameter. Both shafts were used for construction, and the central shaft is still being used today for ventilation. One of the greatest disasters during tunneling was a fire in the surface structures of the central shaft, which took the lives of 13 men working in the shaft.

The west shaft had to be constructed to obtain a working face at the west end. The working conditions were difficult, and several hundred feet of liner had to be constructed by cut and cover, preventing a productive working face from being established at the west portal. The west shaft allowed work to proceed through the more competent, unweathered rock within the mountain, and approximately 350,000 tons of rock were removed at this location.

Contemporary planners were well aware of the potential for muck utilization. A joint special committee of the Massachusetts Legislature conducted hearings in 1853 on a request by the railroad corporation for a loan of two million dollars to continue construction of the tunnel. In the summary of that hearing, the committee ruled favorably on the request and provided the following quotation relative to muck utilization.

> "It is proposed to construct the tunnel with grades, descending on either side from the centre, at the rate of twenty-six feet per mile, which will facilitate drainage and the removal of the rock from the outer faces, as the cars laden with stone will run out by the power of gravity. It is also intended to use the stone at the eastern end, to create a dam and water power upon the Deerfield, and at each extremity to make embankments with stone down the valleys of the Deerfield and Hoosac [2-1]."

More details on muck utilization are provided later in the construction sequence when the engineers began to establish the alignment of the railroad approaches to the tunnel. The following interesting quotation was obtained from the 1867 Commissioner's report on the alignment at the west end of the tunnel.

> "It is understood that Mr. Manning, when at North Adams, surveyed a route in conformity to this suggestion, but believing that a better line could be obtained, I deferred making purchases of land until another survey could be made under my direction, which resulted in the location of a line leaving the Haupt Tunnel lower or farther west, with a view to use the stone debris from the tunnel for embankment, and left a gravel bank between the line and Manning's, to be taken out as required, ad libitum, passing over the Boston and Albany Railroad by a bridge to a tract of meadow land, the refusal of which I have secured until the coming July for two hundred dollars per acre, with a contingent reserve, should the Hoosac River bed be changed, of about one hundred dollars more. The saving of land damages by this line is variously estimated, but will probably be not less than $75,000; while the other line affords but little room for depot purposes. This line has been examined by Mr. A. R. Field, chief engineer of the Troy and Greenfield Road, and is understood, in its main features, to meet his approval."

At the east end of the tunnel, it was important to complete the construction of a bridge over the Deerfield River, "so that the debris from the Tunnel can be used for the large embankment, of some 60,000 cubic yards (cu yd) east of the Deerfield River." Approach fills for this bridge were also constructed with tunnel muck.

The most interesting example of muck utilization was the use of tunnel muck to construct a masonry machine shop at the east portal. Water from the Deerfield Dam was brought 3/4 miles by canal to the machine shop where it was used to power air compressors, lathes and other machines. The following quotation cannot be improved upon as a description of muck utilization.

> "It having been determined to build it, I think its cost can be shown to be not greater than necessary.
>
> The house was located in the only place where it would not be necessary to cut the whole width of the house and canal into a very high bank. It was at the foot of an old, extensive slide."

> "Upon making the necessary excavations, it was found that the bottom was soft clay, and very much to our alarm, that the bottom was rising, and that the avalanche was on the move. It therefore became necessary, in connection with the fact that the water-level of the canal back of the house was to be 30 feet higher than the river and front, to build heavy masonry. The back wall was made 17 feet thick at the bottom, the whole height of the wall being over 40 feet.
>
> It should further be considered that it became necessary to build with the stone from the Tunnel, because none better could be reasonably obtained. The masonry is therefore simply a conglomerate of junks of stone; but, for want of a natural bond, it must have an artificial one, and this could only be obtained by the use of cement in large quantities, and at great cost, because so far from a railroad."

After World War II, material processors began using the stockpiled muck at the west shaft as aggregate for bituminous concrete. A typical crusher facility with dryers and a pugmill was used. Large blocks of rock were broken into particles with a maximum diameter of 8 in. in the primary crusher and a maximum diameter of 3 in. in the secondary crusher. A fine reduction crusher produced a maximum 3/4 in. particle size which was used in the concrete. Operation of this facility continued until 1967 when the available muck was exhausted. Currently, crushed rock is transported to this area by rail at considerably higher cost.

The biggest problem with crushing muck at this site was the presence of debris. One man was constantly employed removing wood and steel from the muck. Steel debris, which was particularly bothersome, consisted of pieces of rail, drill steel, spikes, wheels, and hammer heads. Despite magnetic detectors, the crusher was frequently damaged, resulting in considerable down-time and repairing cost.

2.3 LITERATURE SEARCH

A thorough literature search was conducted to determine current methods for utilization of tunnel muck. The investigation was not limited to construction of U.S. rapid transit tunnels in urban areas, but included a wider range of tunnel types and locations. The range of the study was extended due to the limited amount of published data on muck utilization. Information sources consisted of journals, periodicals, magazines, conference proceedings, text books, and research reports.

Fifty-five articles on tunneling construction were found during the literature search. (The articles are identified at the end of Section 12-References.) Discussion in these articles of muck disposal methods or problems was normally limited to a few brief comments. Muck utilization plans were discussed in only six tunneling projects, three from the United States and three from foreign countries. Information from these six projects is presented in Table 2-1 and in the following paragraphs.

TABLE 2-1. SUMMARY OF LITERATURE SEARCH

Project Name and Location	Type of Tunnel	Excavation Method	Type of Material Excavated	Quantity of Material Excavated	Muck Utilization	Source of Information
Crosstown Wastewater Interceptor, Austin, Texas	Sewer	Drill and blast (Implied, but not stated)	Soft Rock	175.000 cu yd	1) Landfill 2) Subbase material	Fact Sheet 1974 Soil Speciality Conference
Raccoon Mt. Plant, Chattanooga, Tennessee	Pump Storage Plant	Drill and blast	Limestone	Unknown	Coarse filter material for upper reservoir dam	Tunnels & Tunnelling March 1972
Storm Sewer Tunnel Houston, Texas	Water	Cutter Shield	Clay and Sand	45,000 cu yd	Embankment Fill	Civil Engineering September 1964
Sonnenberg Tunnel, Lucerne, Switzerland	Vehicular	Tunnel boring machine	1) Sandstone 2) Sandy Marl 3) Clay Marl	2000,000$^+$ cu yd	Landfill of a nearby lake	Tunnels & Tunnelling September 1973
Railway Tunnel, Vancouver, British Columbia	Railroad	Drill and blast	Grandiorite	80,000 cu yd	1) Embankment Fill 2) Railroad Ballast	Tunnels & Tunnelling November 1972
St. Gotthard Tunnel, Switzerland	Vehicular	Drill and blast	1) Tremola Schist 2) Aare Granite	2,100,000 cu yd	Embankment Fill	Tunnels & Tunnelling November 1971

Case histories describing the utilization of materials produced from building and highway construction and mining activities were also encountered. In many instances, the methods of utilization or testing of excavated or waste materials are similar to the problems related to the utilization of tunnel muck. Several of these appropriate case histories are described following the tunneling case studies.

2.3.1 Tunneling Case Histories - United States

Three case histories of U. S. tunneling projects are summarized in the following paragraphs. Muck was generally used in landfill projects, although in one case the muck was included as a blend material in an aggregate processing plant.

2.3.1.1 Crosstown Wastewater Interceptor, Austin, Texas

The Crosstown Wastewater Interceptor [2-6], begun in September 1972, will reduce potential wastewater overflows entering a nearby lake and will eliminate the need for expensive reconstruction of existing wastewater systems in heavily developed areas between the lake and the interceptor line. The tunnel will be approximately 11 miles long and is divided into two separate contracts; an east half, 5.8 miles long and 96 in. in diameter, and a west half, 5.2 miles long and 84 in. in diameter.

Approximately 175,000 cu yd of soft rock will be removed from the tunnel. Approximately 50,000 cu yd of the muck will be utilized as fill for a proposed treatment plant at the east end of the interceptor. In addition, a local subbase manufacturer is purchasing some of the muck for processing and for use as a blend material with an aggregate subbase. Construction of the project was slightly more than 50 percent complete in June 1974.

2.3.1.2 Raccoon Mountain Pump Storage Plant, Tennessee

In mid-1970, the Tennessee Valley Authority started construction of a 1.53 million kilowatt underground pump storage facility near Chatanooga, Tennessee [2-7]. Excavation of the majority of the underground facilities, which include power plant chambers, transformer vaults, and conveyance tunnels, was through limestone. Tunnel excavation methods consisted of smooth wall blasting, cushion blasting, and line drilling.

Some of the tunnel muck was utilized as coarse filter material for the upper reservoir earth-rock dam. In addition, approximately 2 million cu yd of blast rock were used in the construction of the 9.5 million cu yd earth dam.

2.3.1.3 Storm Sewer Tunnel, Houston, Texas

In early 1964 the Texas Highway Department began plans for a 6974 ft long by 8.5 ft (inside) diameter concrete storm sewer [2-8] to carry drainage water from a depressed section of Highway 59, near the center of Houston. Soil conditions along the pipeline consist of wet sandy clay with interbedded layers and zones of clay and water-bearing sands, deposited on clay banks and sandstone ledges. These conditions required the use of deep wells, air pressure, and chemical stabilization to control the inflow of water into the tunnel.

Excavation was accomplished with an 11.5 ft diameter rotating cutter-type tunneling machine. The muck was temporarily stockpiled adjacent to the tunnel shaft before being trucked to the site of an embankment fill. Approximately 30,000 cu yd of muck were removed from the tunnel.

2.3.2 Tunneling Case Histories - Foreign

Brief discussions of three foreign tunnel case histories are provided below. Landfill was the primary use for muck, but in one case, rock muck was crushed and used as railroad ballast.

2.3.2.1 Sonnenburg Tunnel, Lucerne, Switzerland

Construction of the 1 mile Sonnenburg Tunnel [2-9] began in November 1969, and the tunnel was expected to be fully operational for vehicular traffic by the end of 1975. It consists of twin, two-lane tubes, and it is being constructed through deposits of sandstone, sandy marl and clay marl. Rock cover above the tunnel has varied from 96 to 160 ft.

The two tubes were driven using an innovative tunnel boring machine. After drilling an 11.2 ft diameter pilot bore, the tunnel was enlarged by two successive enlarging machines to 24.6 ft and 33.6 ft in diameter.

A large portion of the more than 170,000 cu yd of muck from the tunnel was used to fill-in a nearby lake. The drilling operations produced particles small enough to eliminate the need for crushing. The article did not mention potential uses of the completed landfill area. The location of the landfill operation influenced the overall tunneling operation. The tunnel was excavated downhill from the south portal in order to avoid transporting muck through the inner city.

2.3.2.2 Railroad Tunnel, Vancouver, British Columbia

A 4568 ft long railroad tunnel [2-10] with a rectangular cross section, 16 ft wide by 24.5 ft high, was completed in Vancouver in early 1973. The purpose of the tunnel is to eliminate a sharp turn in the track alignment. The rock formation through which the tunnel passes is a hard, uniform granodiorite.

Tunnel excavation was accomplished by conventional drill and blast methods. Construction proceeded from both portals simultaneously. Almost all of the 70,000 cu yd of blast rock were utilized at the site. Approximately 50,000 cu yd were used in the construction of the embankments for a nearby culvert, and an additional 20,000 cu yd were processed through a crusher and used for railroad ballast.

2.3.2.3 St. Gotthard Road Tunnel, Switzerland

The St. Gotthard Road Tunnel [2-11] is 10.1 miles long and has an average circular cross sectional of 915 square feet (sq ft). An adjacent safety tunnel has an average cross sectional area of 75 sq ft. Two rock types were encountered along the tunnel route: Tremola schist and Aare granite.

Full-face drill and blast procedures were used for tunnel construction. In a few areas, totaling approximately 0.6 mile in length, poor rock conditions required excavation of a top heading followed by installation of iron arches and excavation of the bottom heading.

Construction of the main tunnel and safety tunnel produced approximately 1.95 million cu yd of blast rock. Some of this rock was utilized as embankment fill for the motorway. The remaining muck was processed through a crushing plant and wasted.

Construction of the main tunnel started from both portals in mid-1969, and the headings met during the summer of 1974.

2.3.3 Miscellaneous Case Histories

The following brief discussions of four case histories describe utilization of materials from building and highway construction.

2.3.3.1 World Trade Center, New York City

The World Trade Center in New York City [2-12] is a complex of structures including two 1350 ft high towers located on approximately 16 acres of land. Foundations for the building are situated on bedrock which is approximately 70 ft below the ground surface. Foundation construction began with the placement of a slurry trench foundation wall around the entire perimeter of the proposed foundation excavation. As the soil within the slurry wall was excavated, tie-back anchors were used to support the wall.

Approximately 1.6 million cu yd of material, consisting mostly of miscellaneous fill, organic and inorganic silt, sand, and small amounts of boulders and blast rock, were removed from the excavation. The excavated material was placed in a landfill site in the Hudson River, immediately adjacent to the World Trade Center. A 2700 ft long cellular cofferdam consisting of 64 ft diameter cells and connecting arches was constructed to contain the fill. The completed landfill area will create 24 acres of land with a value of nearly $90 million.

2.3.3.2 Lake Ariel Highway, Pennsylvania

Recent construction work on the dual lane Lake Ariel Highway [2-13] involved widening and resurfacing 14 miles of roadway. In lieu of purchasing aggregate from a commercial supplier, the contractor decided to manufacture aggregate from blast rock obtained from the highway construction. Using a portable crushing and screening plant, the contractor produced 400,000 tons of subbase material and 60,000 tons of shoulder material at the site in a nine-month period. The plant operation was reported to be 95 percent efficient with only minor breakdowns for maintenance, change of screen cloths, and occasional removal of oversized materials. This utilization scheme drastically reduced transportation costs and provided a surplus of aggregate material for use during resurfacing.

2.3.3.3 Long Beach-Attesia Freeway Interchange, California

Site work for the Long Beach-Attesia Interchange [2-14] required the removal of existing rubble fill. The fill consisted largely of broken concrete from the demolition of streets and sidewalks.

The contractor for the interchange decided to use a 300 ton-per-hour crushing machine to process the rubble fill for use as sub-base material. Material fed into the crushing plant was limited to a maximum dimension of less than 4 ft and consisted primarily of concrete or bituminous rubble that was as free as possible of lumber, steel, dirt and organic matter. The operation consisted of feeding the raw material into a 30 by 42 in. primary jaw crusher and further reducing the material in a cone crusher. A radial stacker was employed in the stockpiling operation to reduce segregation of the minus 3/4 in. particles.

The final product proved to be an excellent material for compaction. A sufficient percentage of fines was produced during the crushing operation which provided an excellent bond for the coarser particles. Unhydrated cement in the concrete rubble also contributed to the bond. Not only did the contractor utilize his own waste material and avoid the cost of disposal, but other contractors in the area brought similar solid waste materials to the site for processing.

2.3.3.4 Nagasaki Airport, Japan

Construction of the 335 acre new Nagasaki Airport [2-15], off the coast of Ohmura, Nagasaki, Japan, required the dumping of approximately 76 million cu yd of blasted rock beyond an island beachhead. Total cost of the airport, scheduled to open in May 1975, is estimated at $69 million.

About 90 percent of the 10,600 ft long by 1400 ft wide airport facility was constructed in 50 ft of water. The remainder of the site is on an existing island which was partially excavated and refilled with the rockfill in order to produce a homogeneous condition throughout the runway, thus reducing differential settlements.

The contractor quarried and hauled approximately 4 million cu yd of rock per month during the 19 month construction period. Rock was blasted from the tops of two rock outcrops, 130 and 200 ft high. Bench blasting was used with cuts averaging 65 ft deep. Fill material was limited to a maximum 5 ton block weight.

Construction procedures consisted of utilizing a pair of mobile pontoon-type jetties to place 3.5 miles of peripheral rock base. Concrete was placed on the embankment facing and the 100 ft wide by 40 ft high (underwater) rock base served as a peripheral form for the remainder of the fill. The landfill was completed by end dumping the rock fill into the water from trucks.

2.4 SURVEY OF CURRENT PRACTICE

A survey of tunneling contractors, engineers, and owners was completed in order to obtain information which was not available in published literature.

More than 40 owners, contractors, and engineers throughout the world were contacted. Many people submitted information on more than one project, and thus 75 job history descriptions were returned. In two instances, the owner, engineer, and contractor each contributed information on the same project; therefore 71 individual projects were actually surveyed. Appendix A contains a list of respondents and a sample survey format.

Job data were categorized into four areas as follows:

a. Project Name and Location

b. Project Description

c. Use of Excavated Material

d. Extent of Planning Effort

Job data were received on 71 tunneling projects (one of which was a subway station), 36 from the United States and 35 from foreign countries, including 23 from Japan.

The information is summarized in Tables 2-2 and 2-3 for the United States and foreign projects, respectively. The data indicate a significant difference between the muck disposal planning efforts in foreign countries and the United States. For example, muck disposal plans were used in a higher proportion of foreign projects than United States projects.

Location	Yes, a disposal plan was prepared
United States	22 percent of projects
Foreign	63 percent of projects

After the case history data were reviewed, the utilization schemes were grouped into three categories: landfill, base and subbase materials, and specialized uses. The landfill category includes use of muck for general fill, backfill around structures, and structural fill beneath buildings. In the majority of cases, the subcategory "general fill" indicates that at present no construction activity is anticipated on the landfill area. The second category includes use of muck for base and subbase materials for highways, roadways, driveway and parking areas, and railroad embankments. The last category contains the specialized uses of muck including concrete aggregate, brickmaking, and erosion control.

TABLE 2-2. SUMMARY OF SURVEY RESPONSES OF CURRENT PRACTICE OF MUCK DISPOSAL - UNITED STATES

NAME OF TUNNEL AND LOCATION	TYPE OF TUNNEL						DESCRIPTION OF EXCAVATED MATERIAL										SUBSURFACE EXPLORATIONS			
							TYPE						CONDITION				PROGRAM CONDUCTED		PROGRAM ADEQUATE	
	SUBWAY	RAILROAD	WATER	SEWER	UTILITY	VEHICULAR	HARD ROCK	SOFT ROCK	SAND	CLAY	SILT	TILL	WET	DRY	MOIST	NO REPLY	YES	NO	YES	NO
BART PROJECT: Broadway & 9th Street - Oakland, California	X								X	X			X		X		X		X	
BART Subway: Colonial to Diamond St.-San Francisco, California	X						X	X	X					X			X		X	
BART Subway: Modoc Ave. to Colonial Way - San Francisco, California	X								X						X		X		X	
Subway Structures: Market Street Line - San Francisco, California	X								X	X						X	X		X	
Calumet Intercepting Sewer: 17 G Chicago, Illinois				X						X					X		X		X	
Calumet Intercepting Sewer 1BE Section A - Chicago, Illinois				X			X								X		X		X	
LaGrange - Brookfield Rock Tunnel - Cook County, Illinois				X			X									X	X		X	
Lawrence Ave. Sewer: No. 1 - Chicago, Illinois				X			X								X		X		X	
Lawrence Ave. Sewer: No. 2-A- Chicago, Illinois				X						X						X	X		X	
Leamington Ave. Sewer: No. 2-D- Chicago, Illinois				X					X	X	X					X	X		X	
Mt. Greenwood: Nos. 1 & 2 - Chicago, Illinois				X			X		X	X						X	X			X
Southwest Interceptor Sewer: SW 13A - Brookfield, Illinois				X			X		X	X						X	X			X
SW Side Intercepting Sewer: No. 13A - Lyons, Illinois				X			X								X		X		X	
PCI 12A: Romeo Tunnel - Fraser, Michigan				X					X	X	X		X				X		X	
PCI 14: Lakeside Interceptor Harrison Township, Michigan				X					X	X	X		X				X		X	
City of Detroit L H1 - Port Huron, Michigan			X				X									X	X			X
MDSH Project No. 1 - Warren, Michigan				X						X			X				X			X
Northwest Area Interceptor Sewer: No. 2 - Cleveland, Ohio				X						X				X			X		X	
South Branch Intercepting Sewer: No. 2A - NY, NY				X			X									X	X			
North Branch Intercepting Sewer: No. 3 - NY, NY				X			X	X			X					X	X			
North River Interceptor Tunnel- NY, NY				X			X									X	X		X	
Wastewater Interceptor Tunnel: Nos. 1, 2A and 3 - NY, NY				X			X									X	X		X	
East Branch Intercepting Sewer: No. 3B - Staten Island, NY				X							X	X				X	X			X
East Branch Intercepting Sewer: No. 3A - Staten Island, NY				X			X		X		X	X				X	X			X
Moss Point Outlet Tunnel - Springfield, Ohio				X				X		X				X			X			X
Mill Run Sewer Improvement - Springfield, Ohio				X			X						X				X		X	
Bowen Haughton Ditch Relief - Toledo, Ohio				X						X					X		X			X
Austin Wastewater Interceptor - Austin, Texas				X				X								X	X			X
Crosstown Wastewater Interceptor Tunnel - Austin, Texas			X					X		X						X	X		X	
Ballston Station- Arlington, VA	X								X				X				X			X
Claredon Station - Arlington, VA	X							X	X	X	X					X	X		X	
Washington METRO A4a - Washington, D.C.	X						X									X	X		X	
Washington METRO A4b - Washington, D.C.	X						X									X	X		X	
Washington METRO A6a - Washington, D.C.	X						X									X	X		X	
Washington METRO D1- Washington, D.C.	X									X							X		X	
Washington METRO D3 - Washington, D.C.	X								X	X	X		X				X		X	

(CONTINUED)

VOLUME OF TUNNEL MUCK (X10^3 m^3)					MUCK TREATED		HOW WAS EXCAVATED MATERIAL UTILIZED?	WAS MUCK SUITABLE FOR STRUCTURAL FILL BENEATH BUILDINGS?	DID OWNER PREPARE A DISPOSAL PLAN?	MUCK SOLD		WAS THE UTILIZATION OF EXCAVATED MATERIAL BENEFICIAL TO THE PUBLIC?
ROCK	SAND	SILT	CLAY	OTHER	YES	NO				YES	NO	
	40		14,6		X		Landfill for ship terminal bldg.	Yes	Yes		X	Yes - create port facilities
60	30					X	Landfill for commercial buildings	Yes	No	X		Yes
	72					X	Backfill on BART structures	Yes	No	X		Yes
	46		15			X	Landfill for industrial buildings	Yes	Yes - by specification		X	Yes
			17			X	Landfill	No	No		X	Yes
118						X	Rough subgrade and fill	Yes	No	X		Yes
113						X	Fill	Yes	Yes - by specification	X		Yes
130						X	Landfill for sub-division	No - too thin and small	No	X		No
			16			X	Landfill for sub-division	No - unsuitable strengths	No	X		No
	2,8	5	8				Landfill	No - unsuitable strengths	No			No
58	0.8		2.7			X	Landfill (sand & clay) base material (rock)	No - Muck not adequate for aggregate due to size and hardness	No	X		Yes
128	0.3		1.4			X	Landfill (sand & clay) base material (rock)		Yes		X	Yes
75						X	Landfill	No - too thin and small	Yes - by specification	X		No
	50	10	40			X	Landfill at gravel pit site	No	No		X	Yes
	15	5	30			X	Landfill	No	No		X	Yes
256						X	Fill	Yes	Yes - by specification		X	Yes - land betterment
			34			X	Fill	Yes	No		X	Yes - land betterment
			10			X	Lake erosion control	No	Yes - by Park Dept.		X	Yes
106				mixed face 3.8		X	Landfill - private use	Yes	No	X		No
43		0.3	–			X	Landfill - private use	Yes	No	X		No
70						X	Landfill	Yes	No	X		Yes
232						X	Unknown - taken to subcontractor	Yes	No	X		No
		3		19.6			Landfill, sanitary landfill (organic silt)	Yes - except organic silt	No		X	No
13,5	8	2		1		X	Landfill - private use	No	No	X		No
25							Landfill - private use	Yes	No	X		Yes
7							Landfill, trench backfill, road and parking lot base	Yes	No	X		Yes
			18			X	Fill - land improvement	Yes	No		X	Yes - land improvement
48					X		Blend material in sub-base	Yes	No	X		Yes
50			7			X	Landfill	No (only 6% suitable)	Yes - no specification		X	Yes - develop disposal areas
	10					X	Backfill on same site	Yes	No		X	Yes
23	42	57	57			X	Backfill	Yes (approx. 40%)	No			No
96					X		Unknown - taken by subcontractor	No - contamination	No			No
58						X	Landfill and quarry fill	Yes - portions only	No			No
230					X		Landfill and roadway base	Yes - too soft for aggregate	No		X	No reply
			24			X	Backfill and subgrade material	Yes	No	X		Yes
	305 - total					X	Fill	No	No		X	In some instances

TABLE 2-3. SUMMARY OF SURVEY RESPONSES OF CURRENT PRACTICE OF MUCK DISPOSAL - FOREIGN

NAME OF TUNNEL AND LOCATION	TYPE OF TUNNEL						DESCRIPTION OF EXCAVATED MATERIAL										SUBSURFACE EXPLORATIONS			
							TYPE						CONDITION				PROGRAM CONDUCTED		PROGRAM ADEQUATE	
	SUBWAY	RAILROAD	WATER	SEWER	UTILITY	VEHICULAR	HARD ROCK	SOFT ROCK	SAND	CLAY	SILT	TILL	WET	DRY	MOIST	NO REPLY	YES	NO	YES	NO
Metro de Sao Paulo - Sao Paulo, Brazil	X								X	X			X	X			X			
Brighton Sea Outfall - London, England				X				X								X	X		X	
Fleet Line and Victoria Line Railways - London, England	X									X				X			X		X	
Tunnel Trunk Foul Sewer - Buckinghamshire, England				X				X		X						X	X		X	
West Hull Main Drainage - Kinston-Upon-Hull, England				X					X		X					X	X		X	
ALB Tunnel - Germany			X					X		X			X	X			X		X	
Holzem Tunnel - Germany						X		X		X			X				X			X
Subway Sector 12/13 - Germany		X					X		X					X				X		X
Yokoshiba Shield Tunnel - Chiba Prefecture, Japan			X						X		X		X					X		X
New Kannon Tunnel - Fukuoka Prefecture, Japan		X					X							X			X			
Ohno Tunnel - Hiroshima Prefecture, Japan		X					X						X				X		X	
Rokko Tunnel - Hyogo Prefecture, Japan		X					X						X				X		X	
Sayo Tunnel - Hyogo Prefecture, Japan						X	X								X		X		X	
Kannon Tunnel - Kitakyushu City, Japan		X					X									X	X		X	
Aoyama - Mie Prefecture, Japan		X					X								X		X		X	
New Aoyana Tunnel - Mie Prefecture, Japan		X					X								X		X		X	
Hori Tunnel - Miyazaki Prefecture, Japan			X				X						X				X		X	
Kanayama - Nagoya City, Japan	X								X		X		X				X		X	
Nagoya City Subway - Nagoya City, Japan	X								X	X			X					X		X
Uramoto Tunnel - Niigata Prefecture, Japan		X						X								X	X			X
Uonuma Tunnel - Niigata Prefecture, Japan		X						X							X			X		X
Bingo Tunnel - Onemichi City, Japan		X					X			X							X			X
Miyakozima - Osaka City, Japan	X								X	X	X		X				X		X	
Osaka City Subway - Osaka City, Japan	X								X		X				X			X		X
No. 2 Inagi Tunnel - Tokyo, Japan		X							X	X					X			X		X
Honden Shield Tunnel - Tokyo, Japan				X					X		X					X		X		X
Itdabashi: Blok - Tokyo, Japan	X								X				X					X		X
Narimaso Blok - Tokyo, Japan	X									X	X		X					X		X
Nishki-Cho Shield Tunnel - Tokyo, Japan	X								X	X	X		X					X		X
Nishiki-Sho - Tokyo, Japan	X								X		X					X	X		X	
Sasago Tunnel - Yamanashi Prefecture, Japan						X	X								X		X		(1)	(1)
Seoul Subway Section 1 - Seoul, Korea	X						X	X	X	X	X						X			X
Interceptores Profundos - Mexico City, Mexico				X					X	X	X					X	X		X	
Northern Link Railway - So-Au, Hua-Lien, Taiwan		X						X								X	X			X
Yonge Subway and Northern Ext: Nos. Y2, Y4 and Y6 - Toronta Canada	X								X	X	X		X				X			X

NOTES: (1) No response to question

(CONTINUED)

VOLUME OF TUNNEL MUCK ($X10^3 m^3$)							HOW WAS EXCAVATED MATERIAL UTILIZED?	WAS MUCK SUITABLE FOR STRUCTURAL FILL BENEATH BUILDINGS?	DID OWNER PREPARE A DISPOSAL PLAN?			WAS THE UTILIZATION OF EXCAVATED MATERIAL BENEFICIAL TO THE PUBLIC?
					MUCK TREATED					MUCK SOLD		
ROCK	SAND	SILT	CLAY	OTHER	YES	NO				YES	NO	
	(1)		(1)				Backfill of subways and subbase for airport	No	Yes		X	Yes
4.5						X	Disposed at sea	No	No		X	No
			30			X	Quarry fill and brickmaking	Yes	No		X	Yes
7			14			X	Landscaping	Yes	Yes - by specification		X	Yes
	3	5				X	Backfill of a railway cutting	No - material too soft	Yes - by specification			Yes
160			(1)				Fill for valleys	No - rock too soft	No		X	No
60			40		X		Highway fill	Yes	Yes - by specification		X	Yes
2	8					X	Stored in borrow area	No	No	X		No
	16	10			X		Landfill	Yes	Yes		X	Yes
243							Landfill and aggregate	Yes	Yes	X		Yes
180				weathered rock 5	X		Landfill for factory buildings	Yes	Yes		X	Yes
200				20			Landfill	Yes	Yes - by owner		X	Yes
155				soft rock 5			Road bed	Yes	Yes		X	Yes
233						X	Concrete aggregate	No comment	Yes - by specification	X		No
228						X	Road bed	Yes	Yes - by specification		X	Yes
220						X	Road bed material	Yes	No		X	Yes
24						X	Landfill	Yes	Yes		X	Yes
	36	4				X	Landfill for 2 story housing	Yes	Yes - by specification		X	Yes
	20		20				Landfill	Yes	No		X	Yes
82.5						X	Railway road bed material	No comment	Yes - by specification		X	No
240						X	Landfill for housing	Yes	Yes		X	Yes
271			24			X	Landfill and road bed material	Yes	Yes		X	No
	17	2	4			X	Landfill for light housing	Yes	Yes - by specification		X	Yes
	31	16			X		Landfill for city park	No - due to wet silts	Yes		X	Yes
	30		18			X	Landfill for housing	Yes	Yes		X	Yes
	5	5			X		Landfill	Yes	No		X	Yes
	70				X		Landfill	Yes	No		X	Yes
		45	45			X	Landfill	Yes	No		X	Yes
	8.5	8.5	8.5		X		Landfill for 3 story building	Yes	No		X	Yes
	14	9.5		5	X		Landfill for office building	Yes	Yes - by specification		X	Yes
200						X	Road bed and landfill	Yes	(1)		X	Yes
800	600	400	200			X	Land reclamation	Yes	Yes - by specification		X	Yes
	161	241	220			X	Fill for highways	Yes	No			Yes
1000						X	Roadway fill for railroad	No comment	Yes - by owner		X	Yes
(1)	(1)	(1)					Landfill	Yes	No	X		Yes

A number of projects used muck for multiple uses. Therefore 81 uses were reported for 71 projects. The percentage distribution of muck for each of the three major categories is shown in Table 2-4. The statistics indicate that muck was used in landfill operations in almost 75 percent of the tunnel projects included in the survey in which muck was utilized. The figures in Table 2-4 show that the popularity of the method of utilization decreased according to the amount of processing required to effectively use the muck.

TABLE 2-4. DISTRIBUTION OF MUCK UTILIZATION METHODS FOR SURVEY OF CURRENT PRACTICE

	Percentage Distribution of Muck Utilization Methods (1)		
Category	United States	Foreign	Combined
Landfill	77	66	72
Base and Subbase	21	26	23
Specialized Uses	2	8	5

(1) Based on 81 case histories reported in a survey of current practice:

U.S. Responses	43
Foreign Responses	38
Total:	81

2.4.1 United States

Forty-three muck utilization schemes were reported from 36 projects within the United States. Table 2-4 shows a breakdown of the general areas. In nearly 80 percent of the cases reported, muck was used in landfill operations. In only one project was muck utilized for a specialized use (i.e. riprap).

A detailed examiniation of the survey data presented in Table 2-2 indicates that 26 out of 33 landfills were not used for a specified purpose. Thus muck utilization in these projects would be more appropriately described as muck disposal. In 22 projects, however, the landfill was considered by the respondent as suitable to support buildings. Hence it appears that tunnel muck is generally suitable for support of structures, but it is not being used for that purpose.

A more positive approach was taken on the San Francisco BART project where commercial office buildings and marine terminals were built on landfills which consisted of compacted tunnel muck. The muck was placed in thin layers and compacted in accordance with a pre-planned specification.

Perhaps this rather poor overall record of muck utilization can be explained by the fact that in only 8 of 36 projects was any plan for muck utilization formulated. In most cases, the tunnel contractor was made responsible for the disposal of material. The tunneling contractor very often passed the responsibility for muck disposal onto a trucking subcontractor. Frequently the owner and sometimes even the tunnel contractor had no idea where the muck was taken for disposal.

2.4.2 Foreign

The utilization of muck in foreign countries followed the same general pattern established for the United States. The distribution of utilization methods, shown in Table 2-4, clearly indicates that landfill was the primary method for utilization of muck in two-thirds of the projects. However, the survey shows a significant difference in the planning effort behind the utilization schemes. For example, almost 50 percent of the foreign landfill sites were designed for a specific construction purpose as compared to only 20 percent in the United States.

The figures in Table 2-4 also indicate that muck was used for base materials and for specialized uses more often in foreign countries than in the United States.

In many foreign countries, especially Japan, the owner retained possession of the muck, and the project specifications called for its specific utilization. This is evident in the questionnaire responses which indicated that in 22 of the 35 foreign tunneling projects, including Japanese projects, the owner developed his own disposal plan. Of the 23 Japanese projects, 16 reported a planned disposal scheme. It appears that Japanese owners make a special effort to utilize excavated materials. The scarcity of land area in Japan may be one reason. Foreign owners also demonstrate more initiative in their use of excavated materials, and use muck in a larger proportion of projects for road and railroad base materials, concrete aggregate, and bricks.

2.5 INTERVIEWS

The following sections of this chapter present summaries of interviews conducted with various United States contractors and governmental agencies and Japanese contractors.

2.5.1 Contractor

During this study, interviews were conducted with several contractors involved in tunnel construction, muck disposal and materials processing. The purpose of the interviews was two-fold: first, contractors were asked to discuss their past experiences with muck disposal and second, they were questioned about their receptiveness to new concepts for muck utilization.

2.5.1.1 Tunnel Contractors

The primary objectives of tunnel contractors are to advance the heading and to complete construction of the tunnel lining system as rapidly as possible. Construction activities not immediately related to these two tasks are assigned secondary importance. Transport and disposal of tunnel muck, once it has been removed from the tunnel shaft, has been consistently relegated to a background position. Moreover, once the project is underway, muck disposal becomes routine, and the details of selection of haul route and disposal site are soon forgotten. Muck disposal is of primary interest during the bidding or negotiation period when the contractor must determine the price and method of muck disposal.

It is important, therefore, that a method for muck utilization be established early in the construction program. If the contract documents contain specific provisions for the disposition of muck then the contractor can easily arrive at a base price for muck disposal. If a disposal site is provided, pricing muck disposal becomes a matter of calculating haul distance and time and balancing the rate of muck production per day against the number of trucks required for hauling. The general contractor might provide trucks from his own fleet or arrange for a subcontractor to supply the trucks. Truck rental agreements can be arranged on an hourly or daily rental rate or on a price per cu yd (or ton) of material.

In most cases investigated for this study, the general contractor negotiated with a number of trucking subcontractors to arrange for muck disposal, typically on a price per cu yd basis. Disposal costs depended on factors such as the subcontractor's work load, equipment availability, disposal sites, permit costs, and regulations governing truck loading.

2.5.1.2 Trucking Contractors

The opinions of trucking contractors generally fell into two categories: (1) those who were in favor of muck utilization and (2) those who were opposed to what they considered interference in their area of expertise. Those in favor cited assistance with obtaining permits and clearances, efficient use of streets, selection of disposal sites, and the provision for nearby stockpiling sites as the advantages of a plan for utilization. Some trucking contractors candidly admitted that they are surprised when owners, especially public agencies, relinquish ownership of a valuable commodity. In general, smaller trucking contractors favor a plan for utilization because it makes the bidding more competitive and broadly based. Large trucking companies have the capital to buy nearby disposal sites and thereby gain a competitive advantage.

Trucking contractors who are opposed to utilization planning state with some justification that they are already muck utilization experts and that they perform this function as inexpensively as possible. They are, in fact, professional expediters who are constantly aware of the supply and demand for construction fill materials. They take a calculated risk to supply the disposal equipment and disposal sites for the duration of the contract in return for the chance to make a profit. Competition limits the amount of profit and generally stabilizes disposal costs. However, when major construction is suddenly initiated in an urban area, the normal supply of trucks and equipment is insufficient, and disposal costs rise sharply.

Through the standard contract "disposal clause," ownership of the muck is implicitly passed on from the owner to the general contractor, then to the subcontractor, and finally to the owner of the disposal site. Ownership of the material means that the subcontractor can sell the material at a profit. Thus if the owner retains ownership of the muck, the subcontractor loses the chance to be paid twice for the same material, once by the general contractor and then for supplying fill material to a customer. Trucking contractors are therefore hesitant to endorse utilization schemes where the owner retains ownership of the muck.

Successful and unsuccessful trucking contractors were interviewed. Although the successful contractors might agree with the concept of muck utilization, for economic reasons they preferred to maintain the status-quo. In some cases, trucking contractors discovered that none of their usual customers were able or willing to buy the muck. The trucking contractor had to either stockpile the material or pay to dump the material at a sanitary landfill site. The profit normally gained on the second sale of the material was lost, and the contractor was forced to operate at a loss. These unsuccessful contractors naturally would have preferred an organized muck utilization program which would have provided a guaranteed income and protection from financial loss.

2.5.1.3 Materials Processors

Potential customers for tunnel muck include manufacturers such as stone or sand and gravel crushing plants. One processer interviewed in the Washington DC area said that he would be willing to accept any so-called waste material for processing in his plant. Almost any soil type would be acceptable and could be used at the processing plant for an aggregate or aggregate ingredient. Although he was not anxious to use peat or other organic materials, he has used such materials in the past to produce loam.

Representatives of the National Sand & Gravel Association commented that waste products such as tunnel muck should be analyzed on a project-by-project basis to determine the potential for utilization as aggregate sources. This analysis is particularly appropriate because the American Society for Testing Materials (ASTM) has recently revised the standard specification for fine aggregate (ASTM C-33). The revision allows the use of fine aggregate, normally concrete sand, which does not meet the standard gradation requirements, provided that the design mix results in an acceptable concrete product. The aggregate must meet all other requirements, such as abrasion and chemical tests. Tunnel muck produced from a soft ground tunnel driven through sand and gravel deposits thus represents a potential source of concrete aggregate.

2.5.2 Government Agency

Representatives of various government agencies on the local, state and Federal levels were interviewed to determine their reactions to the concept of muck utilization. Emphasis was placed on interviews with local transit and planning agencies who are directly involved with mass transit planning.

2.5.2.1 Washington Metropolitan Area Transit Authority

The Washington Metropolitan Area Transit Authority (WMATA) is currently responsible for a large subway construction program. The entire system is 98 miles long with 47 miles of tunnel and 53 underground stations. Fifteen miles of tunnel and 12 stations will be excavated in rock. Although a balanced cut and fill approach to design was adopted for surface construction, the tunnel muck was not initially planned to be used in the new construction.

During the latter stages of design and early construction, an attempt was made to locate possible disposal areas for tunnel muck. Sites in and around Washington DC were investigated and a number of privately owned areas were located, but WMATA decided that it would be unacceptable to supply tunnel muck from a public project to be used to fill private land. Hence, plans for locating disposal sites and utilizing tunnel muck were discontinued and total responsibility for muck disposal was placed on the contractor.

Another attempt was made to develop a disposal plan for dredged materials removed from the underwater crossing of the Washington Channel. A plan was developed, in conjunction with the Corps of Engineers and the National Park Service, to use a disposal site located in the Potomac River near the East Potomac Park. However, these plans were eventually discarded because of environmental restrictions. Once again, the contractor was required to dispose of the muck.

The WMATA experience thus illustrates that the most expedient contractual method for disposal of muck requires the general contractor to solve the problem and dispose of the materials. This approach was adopted in spite of the fact that WMATA favored the concept of muck utilization and tried to plan for muck disposal. Alldredge [2-16] describes some of the individual rock tunnels and stations within the WMATA system. Included are some recommendations based on WMATA experience for improving relationships between owner and contractor. Particular emphasis is on the bidding stages of the work.

Two case histories from the WMATA program were studies in detail and are reported in Section 2.6 of this report. These case studies illustrate the contractor's solution to the disposal problems.

2.5.2.2 City of Chicago

The Department of Public Works (DPW) for the City of Chicago has traditionally been responsible for subway construction. The standard approach for muck disposal, dating back to 1920, has been to let the contractor dispose of the muck. The Metropolitan Sanitary District of Greater Chicago has also required that contractors dispose of all excavated materials. Recently both organizations have become more sensitive to the muck disposal problem as a result of environmental and legal considerations.

The approach of the DPW has been gradually changing to include the following considerations:

a. When objectionable materials such as dredged materials are produced, environmental restrictions will affect the choice of disposal sites.

b. If large quantities of muck are involved, then economic considerations such as haul distance and disposal area will control the designated method of disposal.

Landfill areas along Lake Shore Drive near Lake Michigan have been traditional dumping grounds for subway tunnel muck. In 1920 a landfill was extended 1500 ft into the lake, and additional fill was probably placed in 1939 as a result of subway construction. However, both the DPW and the Sanitary District have completed recent tunneling projects where the contractor was directed to dis pse of the muck. During construction of a two mile section of the Milwaukee Avenue Subway in 1967-1968, the contractor was made responsible for muck disposal.

The City of Chicago Department of Development and Planning has made a concerted effort to organize muck disposal for at least three major construction projects currently under study. A discussion of this planning effort is continued in Section 10-2.

2.5.2.3 City of Boston

The Metropolitan District Commission (MDC) is in charge of developing a water supply system for the City of Boston. The MDC normally requires that the contractor dispose of all excavated materials. No attempt has been made to utilize the tunnel muck since the quantities involved are relatively small.

The Massachusetts Bay Transportation Authority (MBTA) is responsible for an existing mass transportation system in the Boston area which was constructed in the early 1900's. A recent extension has been completed, and additional extensions are planned in the near future.

Specifications for MBTA construction call for the re-use of all suitable excavated materials. Material can only be removed from the site by permission of the project engineer. Provision is made for stockpiling soil or rock which can be used as backfill later in the project. An example of a specification from the Massachusetts Department of Public Works standard specifications (also used by the MBTA) is given below:

> "Disposal of Excavated Materials. All suitable materials obtained from the excavation, or from the removal of present structures shall be used either in the formation of embankments, shoulders, slopes, loam or clay hardening, etc., or for backfill under, over, or around structures, pipe culverts or drains and at such other places as directed and the material shall be placed and compacted in a manner conforming to the specification for the particular type of work required without additional compensation [2-17]."

In general, the suitability of material is determined by its stability and ability to compact. It was reported that re-use of excavated materials produced a substantial cost savings for the MBTA.

The Massachusetts Port Authority (Mass Port), for almost eight years, maintained a continuous landfill operation at Boston's Logan Airport. Landfill was required in order to expand the airport facilities. Since a specific construction contract to obtain all the necessary fill would have been prohibitively expensive, Mass Port adopted a policy of accepting common fill materials for landfill in non-critical areas such as between runways, taxiways, and below major runway areas at depths where surface loads produce negligible stress.

In general, all types of materials were accepted with the exception of those containing excessive amounts of organic matter, wet clay, steel, or concrete blocks larger than 2 cu ft. Some large blocks were accepted, but only in isolated areas or deep in the fill so that they did not interfere with subsequent utility trench excavation or foundation construction. Any contractor in the area having acceptable fill available could participate in the program. The contractor was paid $0.40 per cu yd for material delivered, placed, and compacted as stipulated by Mass Port.

The program was very successful and it benefited both Mass Port and the contractors. Mass Port obtained the necessary fill at a reasonable price, and disposal costs for construction projects in the Boston area were reduced. The following items contributed to the success of the Mass Port effort:

a. Logan Airport was conveniently located.

b. A large class of fill material was acceptable.

c. No time limits were established for fill delivery.

2.5.2.4 City of Buffalo

The Niagara Frontier Transportation Authority (NFTA) has initiated planning for a mass transit system for Buffalo, New York. In January 1974 preliminary subsurface explorations had been completed and an environmental impact statement also had been submitted.

Phase 1 construction of the system begins near the Buffalo waterfront and extends approximately 11 miles northeastward to the

North Campus of the State University of New York at Buffalo. This line has been divided into three so-called corridors: inner, middle and outer. Phase 2 construction will include an extension of the Phase 1 line, the addition of a spur to Tonawanda, and an eastwest line.

The volume of muck from Phase 1 construction was estimated at approximately 950,000 cu yd of soil from cut and cover sections and 510,000 cu yd of rock from a rock tunnel section. The soil was characterized as glacial deposits consisting of glacial till, outwash and lake sediments. The rock is part of the Onandaga Formation which consists primarily of dolomitic limestone. Tunnels in rock will probably be constructed with tunnel boring machines. The groundwater table generally exists within 20 to 40 ft of the ground surface.

Several possibilities exist for the disposal and/or utilization of excavated materials. The Buffalo area has several sanitary landfills which can be used for the most undesirable solid wastes. Also, potential landfill sites owned by NFTA include the airport and the port area, where development is being planned. The use of muck as backfill for the subway itself is feasible depending on scheduling and the character of the soil or rock. One portion of the transit system, the Inner Corridor, appears to have high quality sand deposits suitable for backfill. Placement of compacted fill will be required at one of the transit storage yards. Backfilling of abandoned quarries and the construction of berms around the car yards to minimize visual impact are other potential uses for the muck. The rock muck may also be suitable for aggregate; many existing quarries are mining aggregate of the same rock type found in the subway corridors.

NFTA was interested in controlling the disposal practices of the contractor provided that acceptable contract provisions and job scheduling activities could be established to avoid disputes and claims for extra payments. One possible disposal plan involved the use of NFTA landfill sites, to be used at the contractor's discretion. All permits would be provided by NFTA. Also NFTA would establish fill requirements commensurate with the proposed use for the filled land. Haul routes within the Buffalo area are not expected to exceed 10 miles, and NFTA's sites exist within this range.

2.5.2.5 Federal Railroad Association

Several years ago, the Federal Railroad Association completed a preliminary study of the area between Washington DC and New York City (called the Northeast Corridor) to determine if viable minerals would be encountered during construction of a tunnel between the two cities. The study indicated that only occasional deposits of materials such as asbestos and mica would be encountered and that the mineral value was generally very low. In addition the study indicated that transportation of the material to a market place would result in additional cost which would probably offset any savings that might be realized by using tunnel muck as a raw material. The normal market price for mineral materials would be much lower than the price of materials taken from the tunnel. The only viable use of the material appeared to be for landfill operations.

2.5.2.6 United States National Committee on Tunneling Technology

The Standing Subcommittee No. 4, Contracting Practices, of the U.S. National Committee on Tunneling Technology has prepared a report entitled "Better Contracting for Underground Construction" [2-18]. The purpose of the study was to identify areas of contract practice which should be improved in order to minimize contract disputes. Contractors, engineers, owners, lawyers, and equipment suppliers throughout the United States and Europe were interviewed. As a result of the study, 17 recommendations were prepared affecting items such as changed conditions, differing site conditions, insurance, value engineering, release of all subsurface information and rights- of-way, permits and owner-furnished materials.

Under the permits section, the report states that the owner should continue to obtain all rights of way and easements. In urban areas in particular, the owner should locate sites for storage and work sheds and should obtain the permits necessary to perform work in parks or city streets. Moreover, the recommendations further state that: "Where major borrow or disposal areas are required as a part of the construction project, and if the owner cannot provide such rights-of-way, he should at least study and survey their availability and advise prospective contractors" [2-18]. The problem of locating disposal sites has traditionally been left to the contractor. The contracting practices committee is now indicating that it may be time to break with that tradition. The owner and engineer should take more active roles in the planning for muck disposal or utilization.

2.5.2.7 Environmental Protection Agency

At present the Environmental Protection Agency does not have a direct interest in the problem of muck disposal in urban areas. Their interest has been largely confined to the adverse effects of any operation on the surrounding environment. The most direct effect of muck disposal on the environment is usually contamination of streams by uncontrolled runoff, especially from mining wastes. In general, the Environmental Protection Agency has provided guidelines for runoff control. Specific regulations are prepared and enforced by other Federal, state and local agencies.

2.5.3 Japanese

Representatives of the Obayashi-Giumi Corporation, a leading construction firm based in Tokyo, were interviewed to establish typical muck disposal procedures used in urban areas in Japan. The contractor was able to supply information on 23 tunneling projects. The information came from job files and from comments by the respective project managers. The data was recorded on the questionnaire forms and summarized in Table 2-3.

It is a common practice in Japan for the owner, in many cases the government or a national railway organization, to retain ownership of the excavated materials and to control the location and placement of the material in the disposal area. For example, in 16 out of 23 projects, the contract specifications contained provisions controlling muck disposal. In many cases the disposal area is a landfill project which eventually will become the site for construction of two-story housing units.

The heavy demand for housing sites has forced the planning agencies to utilize all types of fill materials to develop "marginal land." These marginal sites may consist of wetlands or swamps, or may be underlain by compressible soil deposits which have prevented initial, economical development of the site. A combination of woven plastic blankets, plastic drainage wicks, and surcharging has been used to overcome the shortcomings of the sites. At the same time, these design procedures have permitted the use of all types of excavated materials produced from tunnel and general construction activities in the fill.

The marginal sites are often lowlands which require placement of fill to raise the site grade. At the same time, the soils are too weak to support more than a few feet of fill. Placement of more fill would result in rotational shear failures along the perimeter of the embankments. A woven plastic blanket (similar to a large fishnet) is spread over the horizontal surface of the fill to strengthen the fill. These blankets are spaced at vertical intervals of several feet. The height of the embankment can then be built up above the final grade in order to provide a temporary surcharge load.

The temporary surcharge load is designed to subject the soft, compressible foundation soils to a stress level greater than the final housing loads. To accelerate the consolidation (stabilization) process, vertical drainage wicks are pushed through the fill and deep into the foundation soils. The plastic wicks consist of strips of plastic, approximately 6 in. wide and 1/4 in. thick, and up to 90 ft. long which are driven into the ground with a special mandrel. The strips are hollow and contain capillary tubes which permit water to drain rapidly from the compressible soil strata. The rapid drainage accelerates the stabilization of both the foundation soils and the fill materials.

These innovative techniques have permitted the utilization of previously unsuitable muck in landfill projects.

2.6 DETAILED CASE HISTORIES

Three current urban tunnel construction projects were studied to evaluate all phases of the muck disposal process including location of construction site, rate of muck production, disposal methods and costs, utilization plans, and difficulties encountered. Information was obtained through interviews with the individuals associated with the projects and on-site inspections of the construction procedures.

The cases were selected to provide a range in the types of muck encountered (stiff clay to hard rock) and to illustrate muck disposal problems associated with large construction operations. The projects selected are listed below:

a. Contract D4a, Washington DC METRO (a soft ground tunnel in clay and gravelly sand)

b. Contract A6a, Washington DC METRO (a hard rock tunnel machine mined)

c. City Water Tunnel No. 3, New York City (a hard rock tunnel - drill and blast)

2.6.1 No. 1 - Contract D4a, Washington DC METRO

Project Name:	Washington DC METRO Contract D4a
Location:	Washington DC, Southwest Section between 12th and 2nd Streets
Owner:	Washington Metropolitan Area Transit Authority (WMATA)
Contractor:	S & M - Traylor Bros., Inc.

2.6.1.1 Summary

The joint venture between S & M and Traylor Bros., Inc. was the successful low bidder on tunnel Contract D4a for the Washington METRO. The contract documents provided that the contractor was responsible for disposal of tunnel muck. The joint venture then arranged for a subcontractor, Southern Equipment Corp., to handle the trucking and disposal of the tunnel muck. Any attempt to utilize tunnel muck on other METRO projects or in other areas became the responsibility of the trucking subcontractor. Some consideration was given to the use of a portion of the tunnel muck as backfill for another METRO project, but the material proved to be unacceptable and as a result all materials excavated were used in landfill operations. The purpose of the landfill operation was to backfill gravel pits owned or leased by the subcontractor. The backfilling was required in accordance with county regulations for final grading, restoration, and repair of gravel pit excavations.

2.6.1.2 Project Description

The project included 8300 ft of 18 ft diameter single bore subway tunnel and related fan and ventilation shafts and power substations. The tunnel work was carried out from two headings, one identified as the 12th Street heading, where a sand and gravel deposit was encountered, and the second heading from the Second and D Street shaft location, where stiff clay was found. Both tunnels were constructed using bolted cast iron or steel tunnel segments. A general project location plan is shown in Figure 2-1.

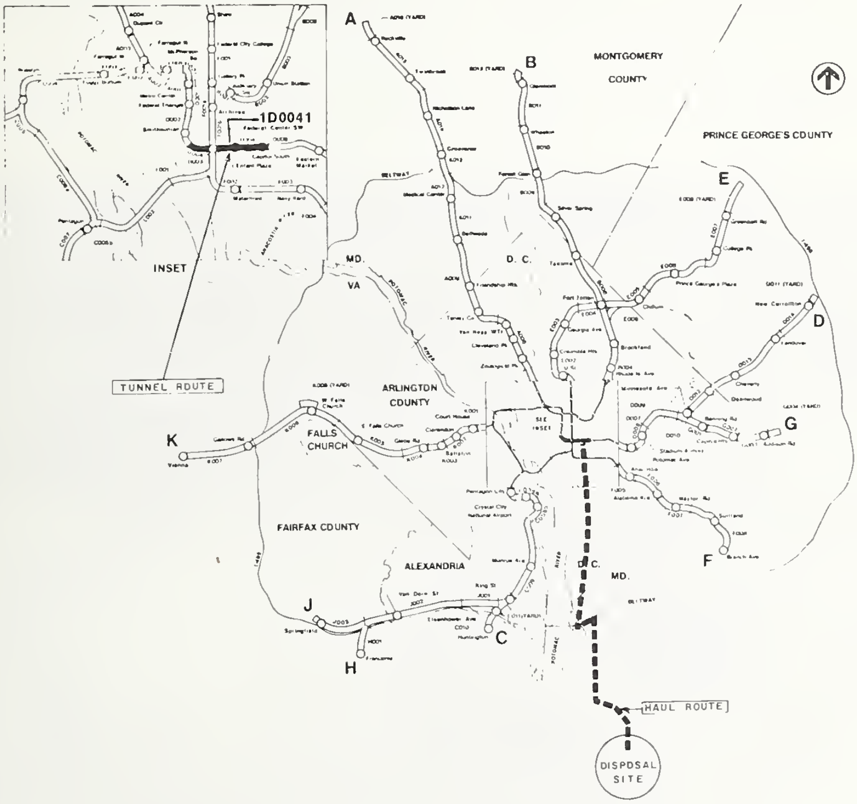


FIGURE 2-1. LOCATION PLAN - METRO CONTRACT D4a
SOURCE: WMATA

2.6.1.3 Geology

Test borings were completed along the proposed route in order to identify the soil and groundwater conditions for the tunneling operation. A detailed discussion of soil conditions along the route was presented in reports by Muser, Rutledge, Wentworth & Johnson [2-19], prepared for WMATA. The profile generally indicated deposits of sand, silty clay, and sand and gravel layers to depths below the proposed tunnel invert. Gravelly sand or sandy gravel deposits were anticipated at the 12th Street heading, grading into more stratified deposits as the tunnel approached the Second and D Street area. At the Second and D Street shaft, however, the soil conditions consisted primarily of stiff, silty clays, both blue-gray and red-brown in color. According to the contractor's records, the soil conditions encountered during the tunneling operations agreed in general with the information provided from the test boring logs. No major unexpected conditions or changed condition problems were encountered.

The groundwater level in the area was predicted to be approximately 30 ft above the tunnel invert. Dewatering operations for the tunnel were considered by the contractor during the initial stages of work. However, due to a delay of almost one year while awaiting the initial shipment of cast iron liner segments from England, the Second and D Street shaft was excavated and stood idle. Work on the cut and cover station section and other private building construction continued and apparently lowered the standing groundwater level along the tunnel route. As a result, during the actual tunnel drive, little or no water was encountered and dewatering was not a problem.

The heading, proceeding from the Second and D Street shaft, encountered several areas of old fill; probably fill placed in old river channels. When these areas were encountered, some loss of ground into the tunnel occurred resulting in surface settlement. However, this loss was not major and caused no excavation or construction delays.

2.6.1.4 Method of Tunneling

The contractor elected to use a Robbins Excavator Shield to work the headings from the Second and D Street shaft. Mining of both the in-bound and out-bound tubes proceeded simultaneously. At the 12th Street heading a Jarva bench shield was installed to excavate the sand and gravel materials. The excavator shields were ideally suited to the stiff clay deposits. A normal cylce, consisting of shoving forward, excavating, erecting the ring, and grouting, consumed about 1.5 to 2 hours. On an average day, consisting of two 9 hour shifts, about ten rings were erected. Each ring was 4 ft wide. Thus, the total volume of excavated material per day was approximately 380 cu yd, measured as volume in place. The excavation portion of the cycle required only 10 to 15 minutes to remove the 40 cu yd of material required for erection of one ring.

The excavator shield was a relatively new concept, consisting of a cylindrical steel shield with hydraulically operated breasting doors around the circumference of the shield. The shield is illustrated in

Figure 2-2. The doors were operated individually in order to provide support of the face and to control the direction of the shield. Excavation was accomplished with a special hydraulically operated excavator arm which rotated about its longitudinal axis and was free to reach any portion of the face. As the material either fell from the face or was dislodged from the face, the back and forth action of the arm also caused a movable flap beneath the arm to scoop the muck material onto a conveyor belt. From the conveyor belt the material was raised near the crown of the tunnel and carried to the muck disposal cars by a second conveyor system.

Six 10 cu yd capacity muck cars were used to carry the muck away from the face. The muck train also included one flat car which was used to bring the liner segments to the face, and to carry the cement and sand required for the grouting behind the liner segments.

A 28 August 1974 visit to the 12th Street heading indicated that little progress had been made since the start of tunneling earlier in the month.

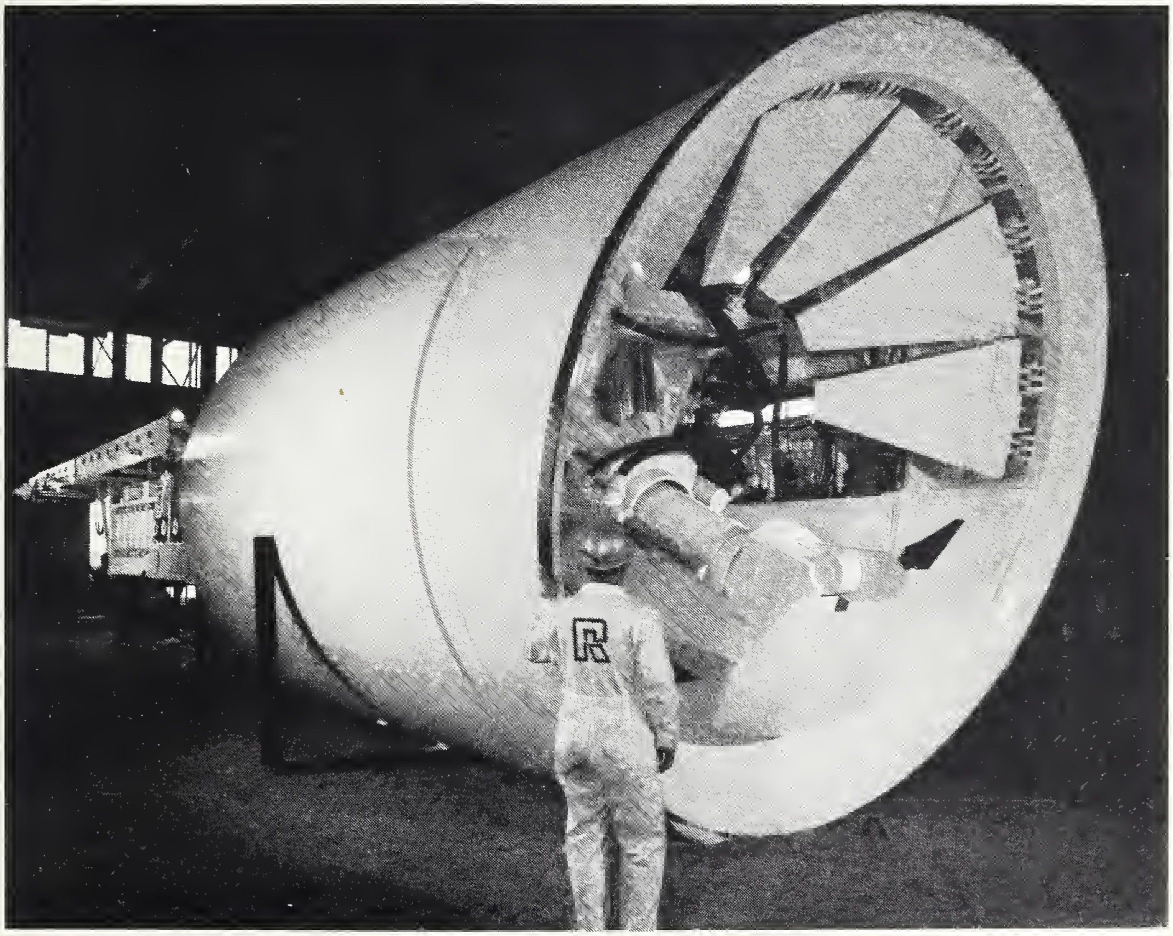


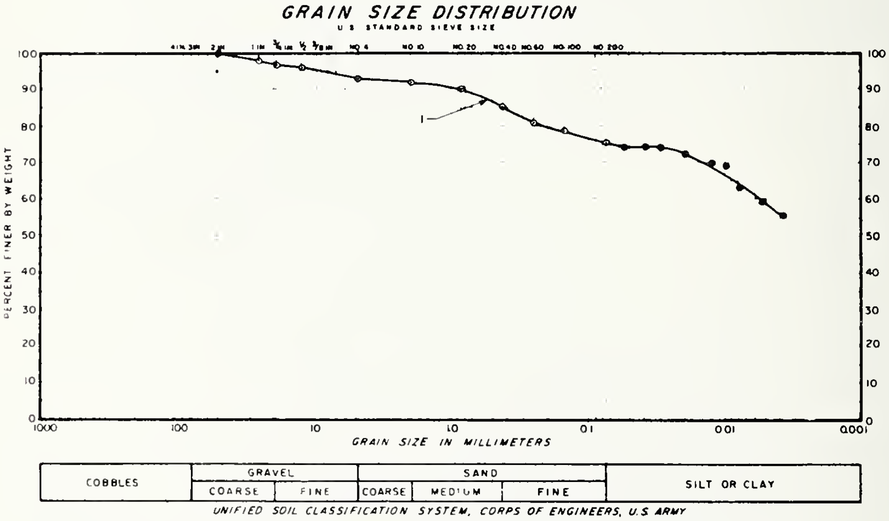
FIGURE 2-2. EXCAVATOR SHIELD
SOURCE: ROBBINS

2.6.1.5 Types of Muck

The muck encountered at the Second and D Street heading consisted of a stiff silty clay, although a soft blue-gray clay was found in some of the old river channel fills. The stiff clay was an excellent tunneling material since it stood freely at the face with a minimum of support. Also the low permeability of the clay restricted the inflow of groundwater. The muck excavated from the face consisted of large chunks of clay grading down to smaller size chunks and chips. The clay was chopped at the face by the excavator arm only to the extent that it was required to reduce the size and allow it to pass the conveyor system and be dumped into the muck cars. At the shaft, the cars were lifted by crane to the surface where the clay was dumped in the muck pile.

The muck pile was also the dumping spot for miscellaneous construction refuse such as cement bags, old pieces of lumber, and miscellaneous construction debris. The refuse was estimated at 2 percent or less of the total volume of the muck pile. However, the debris was a standard by-product of the tunneling process.

A sample of the stiff red-brown clay was obtained, and laboratory tests, including Atterberg Limits, gradation and several shear strength evaluation tests, were completed. The gradation results are shown in Figure 2-3. Based on the test results, the clay was classified as a stiff red-brown silty clay, little coarse to fine sand, trace gravel.



SOURCE: CLAY MUCK FROM METRO CONTRACT D4a

FIGURE 2-3. GRADATION CURVE - METRO CONTRACT D4a

Samples of the sand and gravel encountered at the 12th Street heading were not obtained. However, based on a visual examination, the material was classified as a brown gravelly coarse to fine sand, trace to little silt with cobbles up to 12 in. in diameter.

2.6.1.6 Contract Documents

The provisions in the contract between WMATA and the joint venture required the contractor to assume full responsibility for the disposal of muck outside the limits of the METRO right of way [2-20]. All disposal costs were to be included in the applicable unit prices for excavation of material from the access shafts and the tunnel headings. The contractor then incorporated the same or similar provisions in the subcontract with the trucking subcontractor.

The general contractor awarded the subcontract for disposal of the tunnel muck on the basis of the lowest price per cu yd disposed. Volumes were determined by in-place measurements. In the initial stages of negotiations, approximately six trucking firms were either contacted by the general contractor or submitted prices to the general contractor. After reviewing the initial submission, further negotiations took place and an award was made to Southern Equipment Corporation, the low bid contractor. A standard contract document was drawn up based on the standard American General Contractors Association format.

According to the provisions in the subcontract, the subcontractor was required to obtain all permits for disposal of the muck and was required to maintain sufficient equipment to dispose of the muck as it accumulated in the muck pile at the shaft location. The subcontractor thus provided a front end loader and the necessary truck force to remove the muck material. All of the muck produced from the tunnel then belonged to the subcontractor.

2.6.1.7 Disposal of Tunnel Muck

The subcontractor had two options for the disposal of the tunnel muck: (1) use the material to fill an abandoned sand and gravel pit located in nearby Prince George's County, Md. or (2) use the sand and gravel from the 12th Street heading as backfill for other sections of the METRO system.

The clay muck was never intended or studied for use as a backfill material on the METRO site, nor was it evaluated for use in any brick making plants. However, the sand and gravel deposit at the 12th Street heading was considered a prime source of backfill material for other sections of the METRO construction. Unfortunately, when the sand and gravel material was evaluated for use as backfill, the presence of cobbles precluded the direct use of the muck. The fill specifications limited the maximum particle size to 3 in. The contractor also determined that it would have been too expensive to set up a portable screening plant at the shaft site to process the muck. Thus the subcontractor used the tunnel muck from this contract to fill the gravel pit.

Because the subcontractor was involved in several operations in the city requiring disposal of muck and supply of gravel backfill, the utilization of trucks was a prime factor. For instance, on another contract, Southern Equipment Corporation had to supply approximately 90,000 cu yd of bankrun gravel backfill. This material had to be transported approximately 15 to 20 miles, and trucking was definitely required to bring this material to the city. Normally the trucks would return empty, but since the contractor had several muck disposal contracts in the city, these trucks were used to haul material to the dump sites. By arranging the trucking schedule, the contractor was able to maximize the use of the trucks and thus maximize profit.

2.6.1.8 Disposal Restrictions and Difficulties

In order to dispose tunnel muck from the METRO project, the trucking contractors had to be certain to locate a disposal site. The location of each new dump site became further from the city and thus more difficult to reach. Thus a contractor who owned or obtained access to an old gravel pit within reasonable hauling distance from the city had a competitive edge when bidding for work on the METRO project. However, even though a disposal site was available, the contractor was not without further problems. Some of the difficulties encountered are listed below:

a. The location or access to a gravel pit or other dump area had to be confirmed prior to providing a firm price on the disposal of muck material. In the case of Contract D4a, the contractor leased a section of an old gravel pit which was located in Prince George's County, Maryland.

b. The use of municipal dump areas was almost precluded due to the dump fee which ranged from $9 to $13 per truckload. This fee applied whether or not the material was refuse or tunnel muck which could be used in part of the sanitary land fill operation. Since an average truckload consisted of 13 to 15 cu yd of material, the dump charge added almost one dollar per cu yd to the contractor's disposal price.

c. Normally the contractor maintained equipment at the disposal site. Since storage sheds had to be constructed, an occupancy permit was required from the local authorities. This permit is normally not difficult to obtain.

d. The contractor also had to post a bond with the city or county to guarantee that the highway at the immediate access to the dump site would be maintained in excellent condition. Heavy truck traffic entering and leaving the dump site resulted in additional load on county roads, and any road deterioration had to be repaired by the contractor.

e. Within the city limits there were some general guidelines with regard to street cleaning operations. However, there were no specific requirements such as "the street must be washed down once a day" or "the street must be broom cleaned once a day." The requirements normally stated that the street should be kept neat and orderly at all times. However, government agencies and neighboring building owners were often more insistent that the construction site be kept clean and that less dust be generated. This was often a difficult requirement to satisfy immediately adjacent to a site where trucks were traveling with heavy frequency.

f. The trucking demands varied almost hourly. At any given time a tunnel shield could break down or the excavation process could be terminated and the volume of muck to be removed would then suddenly dwindle to little or nothing. The subcontractor who had planned on an active day's work was thus faced with a fleet of trucks which now had little or no work. For example, on one particular day, the contractor estimated seventeen trucks would be required. But at noontime he discovered that only eight would be needed for the afternoon operations. On the next day eight trucks were continued but seventeen were needed. It was difficult to schedule all of the necessary trucking for a tunnel project.

The fluctuation in demand could have been minimized if larger stockpiles of tunnel muck were created at the various shaft locations so that trucking could continue for at least one or two days from these stockpiles. However, the stockpiles occupied space in an already crowded site, and the tunnel contractor was not willing to forfeit such space.

2.6.1.9 Conclusions

The following conclusions are based on our analysis of muck disposal for Contract D4a:

a. Regulations promulgated by Prince George's County, Maryland, requiring the backfill and grading of sand and gravel pits have prompted one contractor to utilize tunnel muck from the Washington METRO system as sand pit backfill.

b. Site explorations including test borings have predicted the general geology along the tunnel route. The problem of changed conditions has not occurred. However, oversize cobbles were encountered in the sand and gravel deposit and precluded the use of this material as backfill on the METRO project.

2.6.2 Case History No. 2 - Contract A6a, Washington DC, METRO

Project Name:	Rockville Route, Rock Tunnel, Section A6a
Owner:	Washington Metropolitan Area Transit Authority (WMATA)
Contractor:	Morrison-Knudsen & Associates

2.6.2.1 Summary

The successful low bidder on tunnel Contract A6a, a rock tunnel, was Morrison-Knudsen & Associates. According to the contract documents, the contractor was responsible for the disposal of all tunnel muck. The contractor arranged with a trucking broker, Hopkins, Inc., to haul away all muck produced by the hard rock tunnel boring machine (TBM). The trucking broker in turn located a gravel processing plant owner who was willing to accept tunnel muck. The combination of a trucker who guaranteed to haul away the muck plus a guaranteed disposal site allowed the general contractor to proceed with the tunnel excavation.

During the initial stages of portal construction, drill and blast methods were used. The drill and blast rock was used as a lining for a portion of adjacent flood damaged Rock Creek. Samples of the TBM muck were also tested to determine suitability for backfill on METRO construction. One set of tests showed that the muck would be satisfactory for backfill, but a second test proved it would be unacceptable. The variability of the quality of the muck (due to variations in rock quality) prevented its direct use as backfill. Thus all muck was hauled to a rock crushing plant located in Prince George's County, Maryland. The rock was sorted, screened and crushed, and then used for roadway base materials, driveway base materials, or as an ingredient, after additional screening, in the manufacture of bituminous concrete.

2.6.2.2 Project Description

The major items of work included 18,725 ft of single track rock tunnel, 18 ft in diameter; 500 ft of double track rock tunnel; rock tunnel cross-over structures, fan shafts and two station entrances. Figure 2-4 shows the project location plan. Temporary support of the rock tunnel was required in the form of rock bolts. A final lining consisting of cast-in-place concrete was required to complete the tunnel.

Total quantities of materials were estimated as follows: rock muck, 300,000 cu yd; common excavation, 54,000 cu yd; and backfill, 34,000 cu yd.

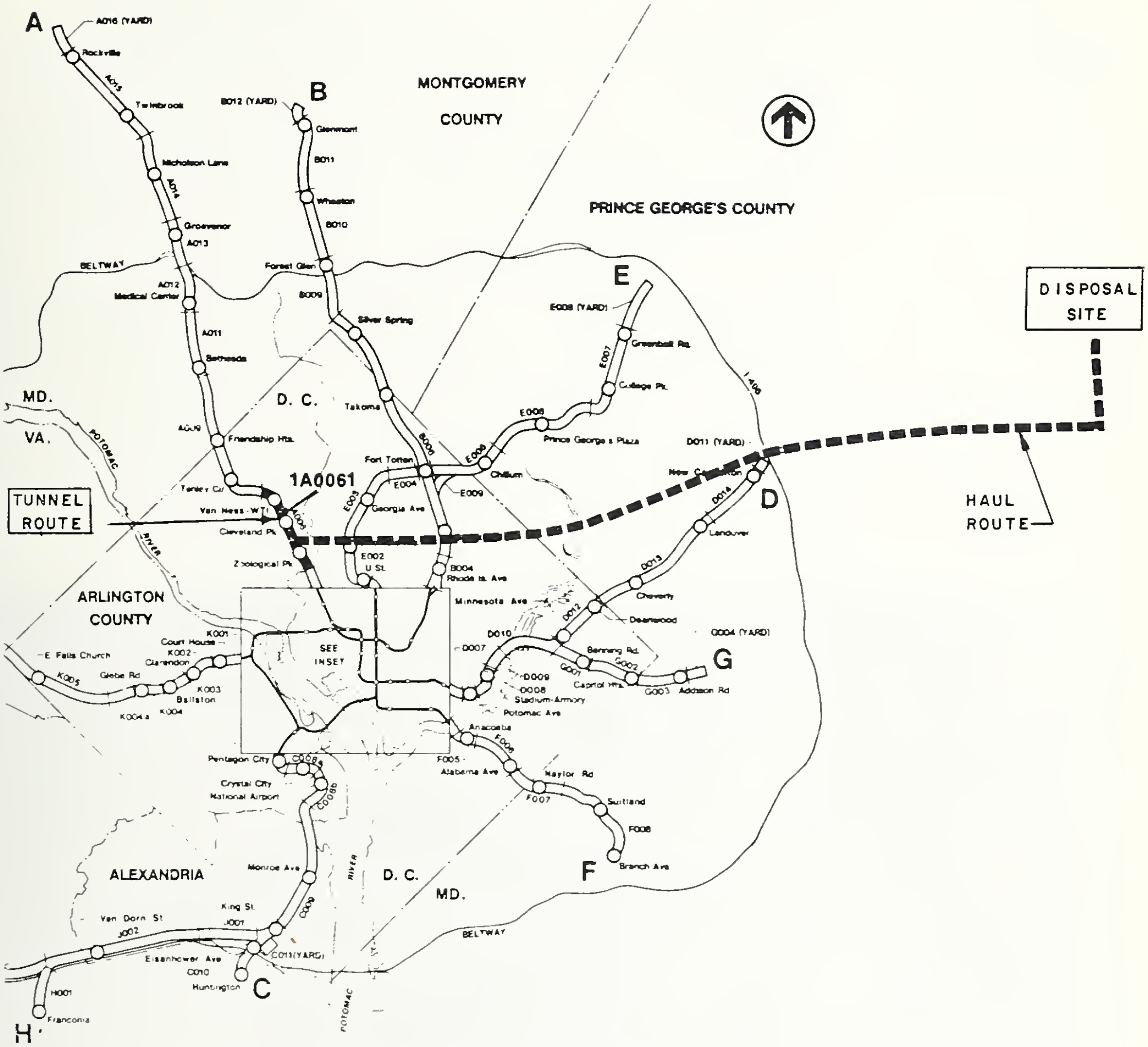


FIGURE 2-4. LOCATION PLAN - METRO CONTRACT A6a

SOURCE: WMATA

2.6.2.3 Geology

Test borings were completed along the route of the tunnel. Soil samples were taken in the sand and clayey overburden soils, and rock core samples were taken of the underlying bedrock. The bedrock was generally classified as a schistose gneiss with chlorite schist also occurring along the route. A detailed discussion of soil properties and rock quality along the route was presented in reports by Muser, Rutledge, Wentworth & Johnson [2-21] prepared for WMATA. With the exception of excavation at portal and shaft areas, the tunnel was located entirely in bedrock.

2.6.2.4 Method of Tunneling

The contractor elected to use two methods of tunneling to excavate the rock. Drill and blast procedures were used to open up the large portal and cross-over areas. A Robbins hard rock tunnel boring machine (TBM), illustrated in Figure 2-5, was used to advance the heading along each of the running sections of the tunnel. A muck train hauled the muck to the portal where the cars were individually tipped over, dumping the muck in a pit excavated adjacent to the track.

In the drill and blast section, steel sets and wood lagging were used to provide temporary support. Overbreak problems were not severe, but were significant when compared to the smooth circular bore produced by the TBM. About 100 ft of the running tunnel were excavated with drill and blast methods before the TBM was mobilized.

The smooth bore section required little temporary support. However, rock bolts were installed in the crown at regular intervals along the route. In several areas, rock falls had occurred and steel sets and lagging were used to shore up these areas.

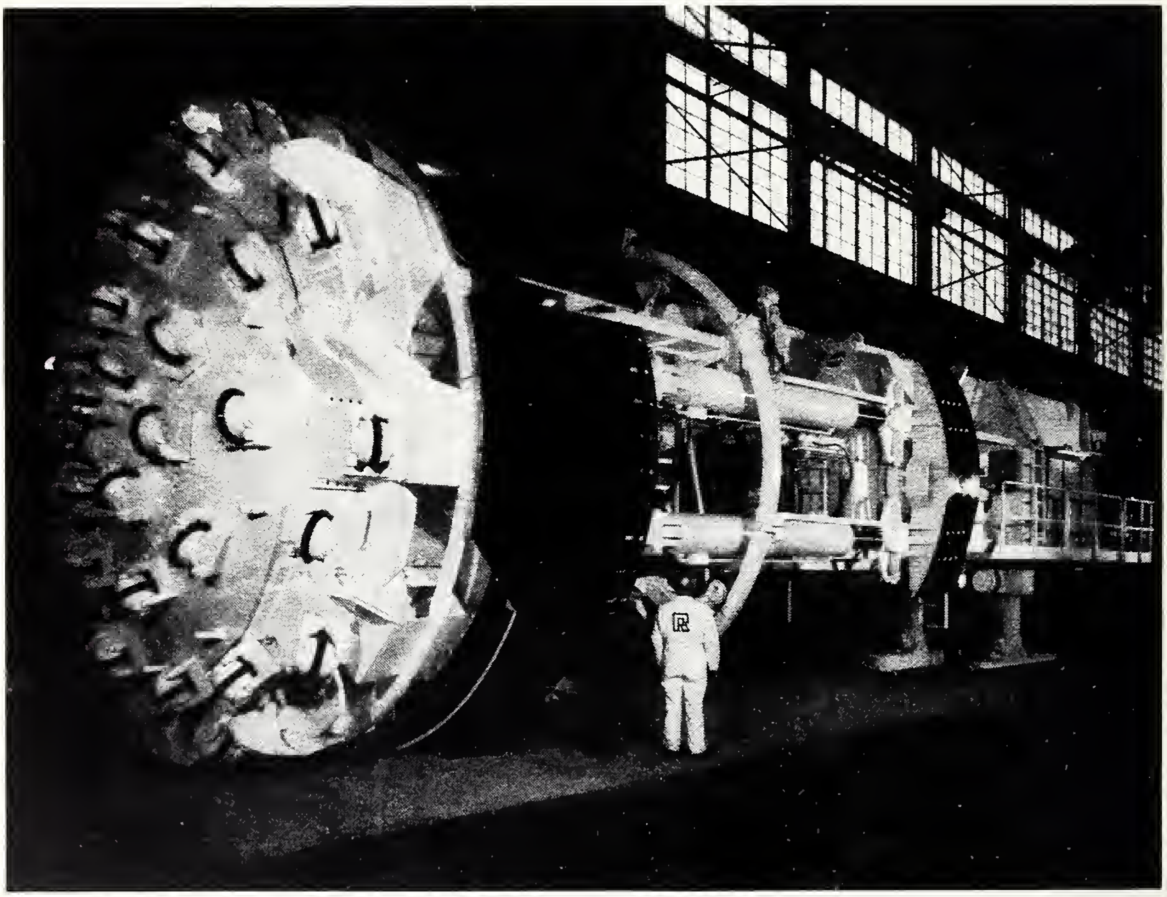
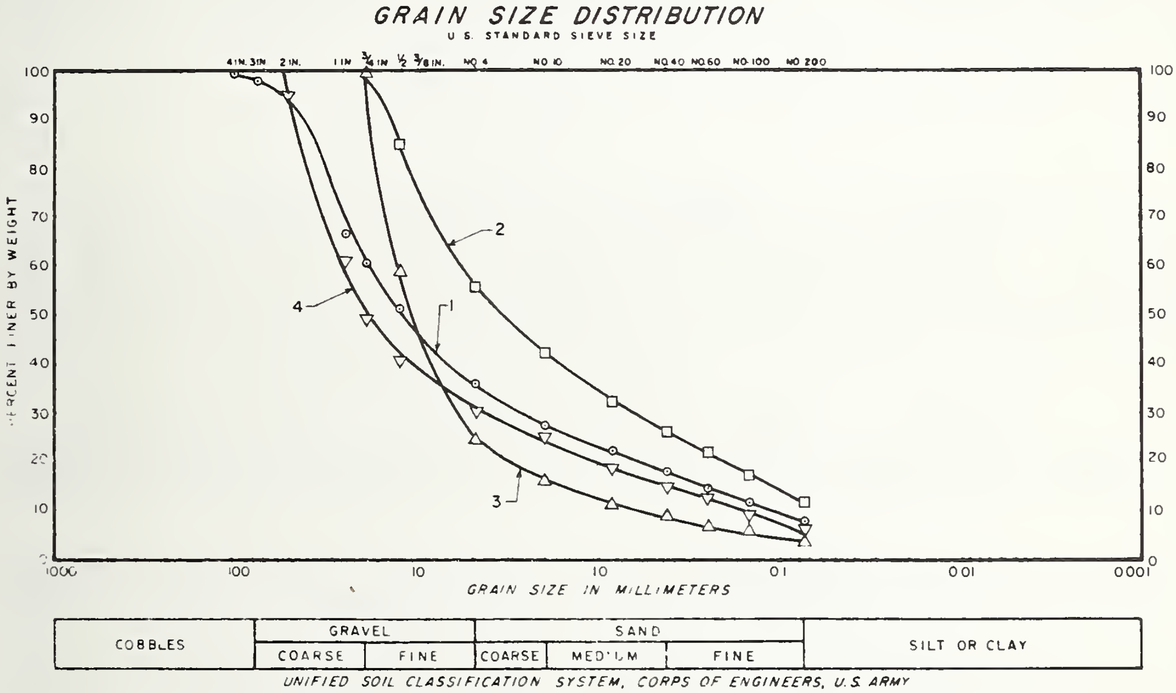


FIGURE 2-5. HARD ROCK TUNNEL BORING MACHINE
SOURCE: ROBBINS

2.6.2.5 Types of Muck

At the start of construction, drill and blast muck was produced. The muck was generally blocky with pieces ranging from 2 x 2 x 2 ft in dimension down to coarse sand sizes. A limited amount of this muck was produced.

The TBM produced a well graded muck with a maximum particle size less than 4 in. and grading down to silt size particles. As the result of the TBM cutter action, the larger rock particles were normally long and flat. Smaller sand sizes were more nearly equi- dimensional. Figure 2-6 shows some sample grain size distribution curves of the rock muck.



TEST NO.	SOURCE
1	ROCK MUCK FROM METRO CONTRACT A6a
2	CRUSHED STONE - A.H. SMITH, CR8 PROCESS
3	ROADWAY SHOULDER MATERIAL (MARYLAND STATE SPEC.)
4	ROCK MUCK FROM METRO CONTRACT A6a

FIGURE 2-6. GRADATION CURVES - METRO CONTRACT A6a

The muck produced by the TBM was usually dry or damp with only occasional water problems at the face resulting in saturated muck. However, during the unloading of the muck cars the muck was dumped into a deep pit which also formed a sump for rainwater. The wet muck was then loaded into trucks by a rubber tire front end loader.

Construction debris consisting of pieces of the TBM, sections of rock bolts, and miscellaneous construction materials were found in the muck piles. However, the total volume was very low, probably less than one or two percent of the total muck volume.

In addition to the rock muck, soft ground excavation was required for a number of vertical fan shafts and at station entrances. Also related utility lines required both excavation and backfill. These quantities, however, were relatively small compared to the overall rock tunnel muck. The estimated quantities of soft ground excavation were about 58,000 cu yd.

2.6.2.6 Contract Documents

The primary contract documents between the owner and the general contractor contained two provisions in separate sections relating to disposal of common excavation materials and underground excavation materials. Common excavation materials applied to materials removed from fan shafts, station entrances and utility work whereas underground excavation was related to tunneling and crossshaft construction. Pertinent sections of the contract read as follows:

> "3.3.5.3: Disposal of Excavated Material (applies to common excavation). Unless otherwise indicated, excavated material shall be disposed of outside of the authority's right of way. When approved by the Engineer, it may be used as fill.
>
> The contractor shall make his own arrangements for disposal of waste material off-site and he shall pay all costs involved [2-22]."

In a similar manner, disposal of the muck excavated from rock tunnels was handled as follows:

> "4.1.11: Disposal of Excavated Materials (from underground excavation). All excavated or spoil material not required for use as backfill or in permanent or temporary fill shall be disposed of in accordance with Section 3.3, Excavation and Backfill [2-22]."

Following the criteria established by these specification requirements, the contractor made arrangements with a trucking subcontractor, Hopkins, Inc., to dispose of excavated materials, including tunnel muck. The contractor did not establish a detailed subcontract document but instead used a simple purchase order agreement to provide for payment to the subcontractor. The purchase order stated that the trucking subcontractor was paid for each ton of material hauled from the site. The subcontractor was entirely responsible for providing the necessary trucks and loading equipment to remove material from the site in accordance with the rate of production of the TBM.

2.6.2.7 Disposal of Muck

Several attempts were made to utilize the tunnel muck in other construction projects. In one case the material was used successfully, and in another case the material was considered unsuitable.

In the first instance, tunnel muck produced from the drill and blast excavation at the entrance portal was used as a riprap lining for Rock Creek. During a hurricane, many waterways in the Washington DC area had been significantly damaged. The repair to these waterways required replacement of riprap, and the sudden demand for riprap reduced the quantity of available stone. At the time that corrective work was underway, almost any type of blast rock was utilized as riprap lining. The restoration work was carried out for the National Park Service, the caretaker organization for the adjacent Rock Creek Park.

The majority of the underground excavation material consisted of TBM muck, a crushed stone product grading in size from 4 in. in maximum dimension to silt size particles. Several uses were considered for this material including surfacing of bicycle paths in the adjacent park area and the utilization of the material as backfill on the METRO project. Neither the bicycle path scheme nor the use of the material on the construction project were adopted.

A series of laboratory gradation and compaction tests was completed on samples of muck recovered when the machine was several hundred feet from the portal.

At the time the machine was boring through relatively hard rock, test reports on the tunnel muck were favorable. It was determined that the material would be used as backfill on the construction project. However, a second series of tests was completed after the machine had advanced a significant distance. At this time the tunnel muck failed to meet the gradation specification requirements for backfill. It was then determined that the muck was too variable in nature to be a dependable source of backfill for the project.

Since the tunnel muck was not approved for backfill, the contractor made arrangements for disposal of the material. The trucking subcontractor, Hopkins, arranged for the material to be dumped at a gravel pit owned by A. H. Smith, Inc. The gravel pit, located in Prince George's County, Maryland, was the site of a processing plant for bituminous concrete and roadway base course aggregate. This site was therefore a guaranteed dump, and material brought to the pit was either stockpiled or immediately started through a processing operation. Particles greater than 3 in. were screened out. Further crushing produced particles with a maximum size of 1.4 or 1.0 in. A sample of the aggregate, identified as CR8 (Crusher Run 8), was tested to determine the gradation; results of the test are shown in Figure 2-6.

2.6.2.8 Disposal Restrictions and Difficulties

No difficulties were encountered in the normal process of hauling muck from the portal to the gravel pit. However, prior to accepting the muck as a raw material, the aggregate processor investigated the quality of the rock by performing tests on core samples of the rock. The samples were crushed and sieved and tentatively approved as an aggregate source.

In order to use the material on roadway construction, the processor had to obtain initial approval of the local highway departments and then maintain the quality of the aggregate. Initially an extensive series of tests was completed on the processed muck to evaluate qualities such as gradation, particle shape and hardness (by the Los Angeles Abrasion Test).

The gradation of the untreated muck was generally acceptable, but the particle shape was unacceptable. The long, thin particle shape produced too many "flats", smooth surfaces which provide a low skid resistance in pavement surfaces. However, after crushing to a maximum particle size ranging from 1.5 to 1.0 in., the flats problem was eliminated. A random sample of roadway shoulder material used on local county roads was tested to determine the as-built gradation. Note that the gradation curve, shown in Figure 2-6, is similar to the gradation of the raw tunnel muck with the exception that the largest particle size of the roadway sample is only 3/4 in. compared to 3 or 4 in. for the muck.

The muck generally satisfied the hardness requirements. However, as the TBM mined through soft or weathered rock in the tunnel, the quality of the muck declined. The operator of the TBM could sense the variation in rock hardness by observing changes in the hydraulic pressure gauges and power consumption. The information that the muck was soft was passed along to the gravel pit operators who sorted the poor quality muck into waste piles.

The processor also discovered metallic debris in the muck. Debris consisted of rock bolts, parts of equipment (such as bolts, cutters, and cutter holders), and miscellaneous field tools. It was necessary to install an expensive electromagnet over one of the belt conveyors in order to remove steel debris before the muck entered the stone crushing equipment. Prior to installation of this magnet, severe damage occurred when parts of steel bolts and other equipment became caught in the stone crushers.

Non-magnetic debris such as timbers, rubber boots and miscellaneous construction debris also occurs in the muck. On occasion this material passes through the crushers but does not greatly damage the crushers or significantly change the muck property. An attempt was made to remove this debris prior to the crushing process.

2.6.2.9 Conclusions

a. The drill and blast muck produced from the initial portal excavation was utilized for riprap to repair storm damaged Rock Creek. Rock Creek was located in the park area immediately adjacent to the tunnel portal and thus provided an ideal utilization plan for the coarse muck.

b. An attempt was made to utilize the raw tunnel muck produced by the tunnel boring machine. Plans for utilization of the muck were discarded, however, when laboratory tests indicated that the rock muck was too variable to provide a reliable hard crushed rock fill material.

c. The tunnel muck was successfully sorted and crushed by an aggregate processor and was used in bituminous concrete pavements and as a roadway base course material.

2.6.3 Case History No. 3 - City Water Tunnel No. 3., New York City

Project Name:	City Tunnel No. 3
Owner:	Board of Water Supply, New York City, New York
General Contractor:	Water Tunnel Contractors

2.6.3.1 Summary

City Tunnel No. 3 involved the construction of about 14 miles of water tunnel, ranging in diameter from 10 to 24 ft, plus numerous access shafts and three major valve chamber caverns. The tunnel is located in the New York City area and extends from Yonkers, southerly through Manhattan, ending in Queens, New York. The job was originally divided into three separate contracts identified as Nos. 520, 521 and 522. Water Tunnel Contractors, a joint venture group, was formed by Dravo, Groves, Ostrander, Dickson, Arundel and Walsh. Construction started in 1970 but was halted in 1974 pending the settlement of a contract dispute.

Approximately 2 million cu yd "solid" muck were to be removed during the construction, including the tunnel and related chambers and access shafts. The muck was removed from three access shafts located in Van Cortland Park and High Bridge Park and on Welfare Island. According to the contract documents, the contractor was responsible for the disposal of all tunnel muck. The contractor elected to use both ocean dumping and landfill for disposal of the tunnel muck. The general contractor and trucking subcontractors located landfill sites for muck disposal. Generally the sites were located within a radius of about 20 miles from the main shafts. The costs of trucking prohibited the disposal of the material at more distant sites.

2.6.3.2 Project Description

The construction of City Tunnel No. 3 was divided into three contracts. Each contract involved tunneling work plus construction of various chambers and riser shafts. An overall site location plan is shown in Figure 2-7. The work involved in each of the contracts is described briefly below:

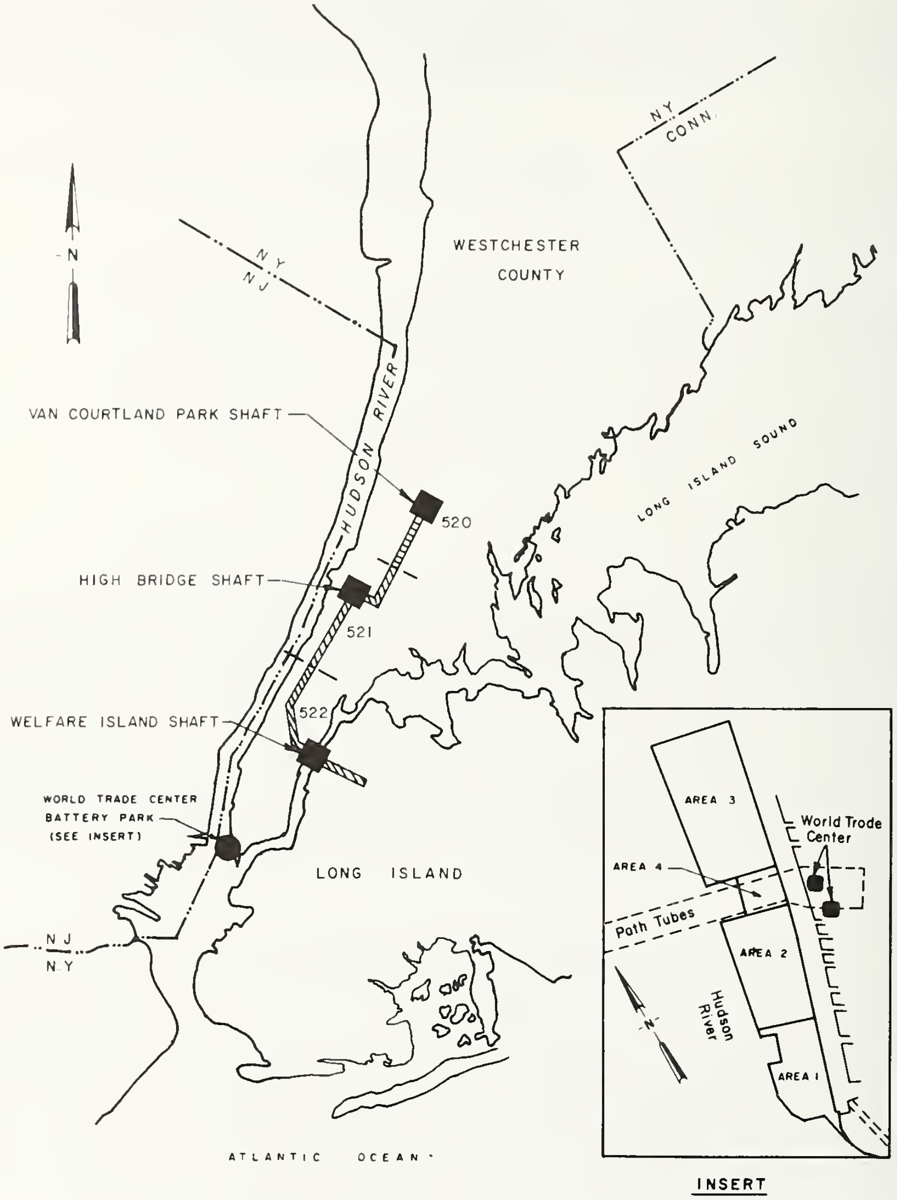


FIGURE 2-7. LOCATION PLAN - CITY WATER TUNNEL NO. 3

a. Contract 520. This contract involved construction of 17,700 ft of concrete lined pressure tunnel, 24 ft in diameter. A major shaft and valve chamber was also constructed in Van Cortland Park. The valve chamber dimensions are approximately 44 x 44 x 620 ft with an adjacent 18 x 17 x 620 ft collection pit. The valve chamber is 250 ft below ground surface.

b. Contract 521. This contract involved construction of 31,370 ft of concrete lined pressure tunnel, 24 ft in diameter. Numerous shafts and a small chamber were also to be constructed.

c. Contract 522. This contract involved construction of 23,150 ft of concrete lined pressure tunnel. The majority of the work involved the construction of a 20 ft diameter pressure tunnel while a section called "The Lower Manhattan Spur" was to be built as a 10 ft diameter tunnel. Two major valve chambers were to be constructed. The Central Park valve chamber was set 170 ft deep in rock with dimensions of 55 x 73 x 70 ft with an adjacent riser valve chamber measuring 20 x 36 x 60 ft. The Welfare Island chamber was also in rock at a depth of 150 ft and measured 60 x 70 x 122 ft with two small adjacent access chambers.

Three major work areas were provided in the contract documents. At each of the major locations an access shaft was constructed to provide access for men and materials and for the removal of tunnel muck. The major work areas are identified as follows:

a. Contract 520: Van Cortland Park

b. Contract 521: High Bridge Park

c. Contract 522: Welfare Island

2.6.3.3 Geology

The contract documents provided test boring information and rock core data along the entire route of the tunnel. The test boring and rock core data identified five major rock types along the proposed tunnel route. The rock types included manhattan schist, yonkers gneiss, fordham gneiss, limestone, and ravenwood granodiorite. The borings, however, were not able to delineate the precise location of the contact areas between major rock types. The major portion of the work typically involved excavation of shafts and tunnels in rock, to depths of up to 600 ft below ground surface.

2.6.3.4 Method of Tunneling

The drill and blast method of tunneling was selected to excavate these large bore tunnels. Rail mounted drill jumbos were used to drive headings from each of the main access shaft locations. Two headings were driven from the High Bridge shaft as well as from the Welfare Island shaft. The following paragraphs describe mining and muck disposal operations conducted at the High Bridge shaft.

Blasting of a normal round usually advanced the face about 8 ft. Approximately two rounds were obtained per working shift. The heading was driven as a horseshoe shaped tunnel with a circular lining to be constructed later. Temporary support of the tunnel was provided by vertical steel sets or posts and circular arch beams spaced approximately 4 ft on centers. Both steel lagging and wood blocking were used to provide support of the rock mass.

The jumbo was also equipped with portable rock drills for installing rock bolts which were used to stabilize the wall plate girders and the steel sets. In addition, portable rock drills or "jackhammers" were used to chip away rock to provide a sound, positive support for each of the vertical wall posts at the invert of the tunnel.

The muck was loaded by a Conway Mucker. A muck train, consisting of six cars, was drawn by a diesel engine to the High Bridge shaft, a 20 ft diameter shaft about 600 ft deep. A single skip bucket with a counter balance was used to hoist the muck from the bin at the bottom of the shaft to the head frame at the surface. The rock muck at the surface was dumped into a bin area adjacent to the shaft at which point a front end loader was used to load ten wheel trucks for removal of the muck from the site.

At two locations, marine disposal of the muck was possible. The High Bridge Park and the Welfare Island Sites were both equipped with a conveyor system which enabled the direct loading of muck from the shaft locations into ocean going scows. The scows would then be towed to approved dump sites.

2.6.3.5 Types of Muck

The drill and blast technique used to advance the tunnel produced a tunnel muck which varied in gradation from large blast rock, about 2 ft in largest dimension, to fine sand particles. The type of rock encountered during the drilling generally resulted in sharp angular fragments of rock. When driving the southerly heading from the High Bridge shaft, very little water was encountered, and the muck was generally handled in the dry state. Water was encountered in driving other headings and required substantial pumping efforts.

When tunneling was progressing at the full capacity at each heading, muck was generated at a combined rate ranging from 2000 to 4000 cu yd per day.

2.6.3.6 Contract Documents

The contract documents contained provisions affecting three general areas of the disposal process:

a. The requirement that a contractor dispose of all tunnel muck.

b. The provision that the contractor obtain land use permits at the access shaft site.

c. The requirement that a contractor obtain all the necessary permits for trucking or disposal.

The requirement that the contractor dispose of all tunnel muck was a standard contract item for most tunnel work in New York City. In this case, the wording in the contract required the contractor to dispose of the tunnel muck outside the limits of work for the tunnel, and also required that the expense for removal of tunnel muck be included in the unit price for excavation of the tunnel.

The land around each of the access shafts was owned or under the supervision of other city agencies. The New York City Park Department owned the land in Van Cortland Park and at the High Bridge Park Site. The amount of land made available to the contractor as a work area in each park was generally limited to the minimum necessary to conduct the work at the shaft sites. Additional land for storage of tunnel muck was not provided.

Trucking activities were restricted by permits to nighttime work. The reasons given for this restriction were based on noise and general construction interference with city traffic. The contractor was thus forced to remove muck by trucks between 8 p.m. and 6 a.m.

2.6.3.7 Disposal of Muck

During the course of the job, muck disposal at times became a critical problem. Storage areas at each of the main shaft locations were limited. As a result, only one or two days' production of muck could be retained at the shafts. If the muck were not removed, then the tunneling activities would have to be shut down.

In the early stages of the operation, muck was disposed of at sea. Bad weather caused problems for disposal at sea and resulted in scheduling problems for muck disposal. In order to avoid this problem, an engineer was assigned to the full-time job of insuring scheduled disposal of the tunnel muck. Trucking and ocean dumping were adopted as alternative methods of disposal. The method of muck disposal was often a balance between either the net costs or loss on the sale of tunnel muck versus the guaranteed loss and scheduling problems if the tunnel works had to be closed down.

Disposal sites for the drill and blast muck included ocean dumping, stockpiling of fill at a quarry in Westchester County, landfill operations in the meadow lands in New Jersey, and use of material as fill in the extension of Battery Park at the lower tip of Manhattan. Tunnel muck was used as rock fill in Area 1 of the Battery Park project. The location of the fill area in the lower west side of Manhattan is shown in Figure 2-7. According to the Battery Park specifications, rock fill could not contain particles greater than 9 in. in maximum dimension. The contractor for the Battery Park work accepted the rock muck as a raw material and then set up a portable crushing plant to crush the blast rock to the specification tolerances.

Through fortunate circumstances, some of the rock muck was also used to construct a compacted fill pad to support the foundations for two 13-story apartment buildings and a related garage and day-care center, as shown in Figure 2-8. A Housing Project in Yonkers, New York was located on a low-lying site covered with a layer of miscellaneous fill up to 8 ft in depth. The project engineers recommended to the New York State Urban Development Corporation that the fill be excavated and replaced with a compacted fill [2-23]. The shot-rock or rock muck from the tunnel was placed and compacted with standard earth moving equipment illustrated in Figure 2-8c. Settlement monitoring during construction and for a short period after construction confirmed the predicted negligible building settlements. Spread footings were constructed on the fill using an allowable bearing pressure of 4 tons per square foot (tsf). The use of rock muck resulted in a significant cost saving over other processed fill materials which were available.

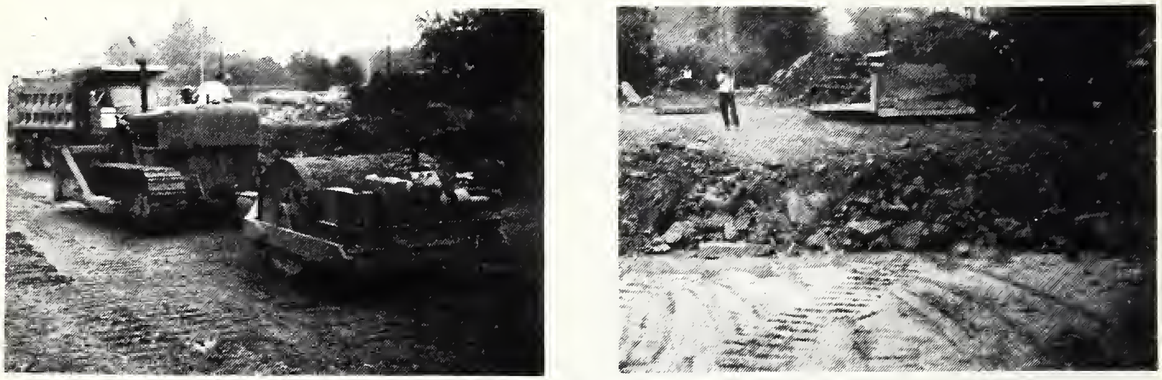


FIGURE 2-8a. WHITNEY M. YOUNG, JR. APARTMENT COMPLEX

FIGURE 2-8b. PLACEMENT OF ROCK MUCK

FIGURE 2-8c. COMPACTION OF ROCK MUCK WITH VIBRATORY DRUM ROLLER

FIGURE 2-8. HOUSING DEVELOPMENT, YONKERS, NEW YORK

SOURCE: LANGAN ENG.

2.6.3.8 Disposal Restrictions and Difficulties

Unless the muck produced during the daily tunneling activities was continuously disposed of, the tunnel job would have to be stopped. In order to maintain this disposal process, the contractor worked on a full time basis to arrange disposal sites for the material. Due to the relatively long duration of the job and the high volume of muck which was produced, no single landfill site was able to absorb the entire volume of tunnel muck produced from these contracts. The contractor therefore arranged for numerous disposal sites through public and private sources. Some of the more significant problems affecting muck disposal were:

a. Location of a site storage room

b. Location of a "dependable" disposal site

c. Cost of disposal

d. Establishment of contract agreements for disposal sites or services

e. Weather

f. Equipment maintenance

g. Permit restrictions

On-site storage of muck was very limited. Only one or two days' production of tunnel muck could be stored in the muck bins at each of the access shafts. Without additional room for the temporary storage of the tunnel muck, the tunnel job would have to be shut down.

The location of dependable disposal sites for the tunnel muck was controlled to a great extent by the ability of the contractor to locate such sites either through private trucking contractors or through a general knowledge of construction activity in the New York City area. Locating these sites was a full time job. Sites for the entire muck volume were not located during the bidding period. Since the entire tunneling production schedule was contingent on muck disposal, the dependability of access to the disposal site was very critical and often superceded the problems of disposal cost.

The cost associated with muck disposal depended very much on the market value of fill materials. The supply and demand for fill in and around the New York City area fluctuated with construction activities. When fill material was in demand, the contractor was able to supply fill and receive a satisfactory price for the material. This price would generally cover the disposal or trucking costs. At other times when construction activities were slow, the muck would be considered a waste material and the contractor would have to absorb part or all of the costs of disposal of the material in order to be sure that the tunnel construction would proceed. Generally the costs associated with trucking limited the sale of muck to an area within 20 miles of each access shaft. Beyond this point, the additional cost for trucking would drive the prices above the price for material which would be commonly available in the area.

One of the important aspects of muck disposal was the rapid response to a request to supply fill to a particular site or to supply a particular trucking subcontractor. Normally these agreements had to be confirmed within a short time period, varying from one to three days, or else the disposal opportunity would be lost.

The weather was also an important factor. At the two sites equipped with marine disposal, the barging method was used initially to dispose of the muck. However, during the winter months, storms at sea could either prevent the barges from being towed to the disposal area or else, once the scows were at sea, a fog might roll in, forcing the scows to be temporarily tied up at a safe harbor location. Also, the rental cost of the scows and tug boats had to be absorbed while they were sitting idle. Thus, the addition of truck disposal methods at the two marine sites provided the contractor with the option of either trucking or barge disposal. When bad weather, such as snow, would prevent trucking operations, the contractor could resort to the scow and barging techniques. The existence of alternate methods of disposal was also an advantage to the contractor in negotiating prices for trucking services.

The relatively small work site around each of the access shafts made it difficult to load large numbers of trucks in a short period of time. Thus it was necessary to have all equipment in good repair. A breakdown of a piece of loading equipment would be a very serious failure in the disposal sequence. For example, disposing of several thousand yards of muck required a truck to be loaded every three or four minutes. The breakdown of either loaders or trucks then represented a real problem.

Usually it was not a problem to obtain the necessary permits for trucking over city and state roads. The only regulation which greatly affected the muck disposal was the requirement that the trucking operations be conducted at night.

2.6.3.9 Conclusions

a. Muck disposal in a major metropolitan area can be a serious problem to a tunnel contractor.

b. The bidding period does not always provide sufficient time for a contractor to line up all of the muck disposal sites needed to complete a major job.

c. The contractor must be able to respond quickly to negotiate agreements for muck disposal sites in order to continue tunneling operations.

d. A muck utilization program could account for part of all of the muck produced from a particular job. If only part of the muck were included in the utilization program, then the program should contain a flexible schedule. Thus, the tunneling contractor would have the chance to minimize disposal costs be either using the programmed site or else selling the muck, depending on the supply and demand for fill.

e. Provision for additional temporary storage at access shafts would be helpful in scheduling the trucking and providing a temporary stockpiling area for tunnel muck should disposal operations be hampered by weather or other unpredictable factors.

3. TUNNEL CONSTRUCTION EQUIPMENT AND TYPICAL MUCK PROPERTIES

3.1 INTRODUCTION

In addition to the type and condition of in-situ soil or rock, the physical characteristics of tunnel muck also depends on the excavation method. For example, a particular rock fragmentation from the drill and blast method may be required to obtain a muck gradation which can be easily removed from the tunnel.

This section contains descriptions of some of the typical types of construction equipment and techniques employed in tunnel excavation and muck removal. The emphasis has been placed on describing those facets of each technique which have the greatest influence on the muck characteristics.

3.2 ROCK TUNNEL BORING MACHINES (TBM's)

Rock tunnel boring machines or TBM's have been developed in an attempt to increase the tunneling rate through more efficient rock excavating processes [3-1, 3-2]. Ultimately, machines may be developed which will permit simultaneous and continuous excavation and liner construction activities [3-3]. The emphasis to date has been placed on the excavation process with the result that many TBM's have been manufactured and used successfully in rock tunneling projects [3-4].

3.2.1 Cutter Design

Cutters for tunnel boring machines are designed to excavate rock by minimizing the "specific energy" or work per unit volume of excavated rock. An individual cutter is normally wedge shaped with a relatively sharp point or with carbide buttons which are designed to initiate failure in the rock by creating a high contact stress. When the stress exceeds a critical value, the cutter displaces a volume of rock equal to the volume of the cutter entering the rock plus a volume of rock which has spalled away from the cutter. After indenting the rock surface, the shape of the tool is then designed to burst the rock adjacent to the cut. The bursting occurs by exceeding the tensile strength of rock particles. The indentation process is inefficient, but the bursting process is efficient. The size of the muck particles is thus basically controlled by the bursting process. The indentation formed by the tracking of the bit is referred to as a kerf.

Laboratory [3-5, 3-6] and field observations [3-7, 3-8] have been conducted to evaluate the performance of individual cutters and the assembly of cutters mounted on a TBM. Both small scale cutters and full size TBM cutters have been laboratory tested. Small scale disc cutter test results have confirmed that the width of a cut is obtained by overcoming the shear and tensile forces in the adjacent rock [3-6]. The width of a cut is almost independent of the angle of the cutting edge of the disc. Full scale laboratory tests of cutters and field observations have confirmed that optimum cutting can be obtained by varying parameters such as thrust, cutter spacing, and cutter diameters.

The chipping or indenting process is aided by the presence of minute flaws or joints in the rock. Thus theoretically cutters should be designed to cut a kerf large enough to encounter several flaws. Estimates place this depth from 0.4 to 1.0 in. In practice, however, it is difficult to chip rock to these depths. The normal cutting depth is usually an order of magnitude smaller.

A TBM is designed with multiple cutters spaced at different radial distances from the center hub of the machine. Typical rock TBM machines are illustrated in Figures 2-5, 3-1 and 3-2. The spacing between cutters, or kerf spacing, is determined by factors such as the normal thrust and torque capacity of the machine and the strength of the rock. Normally only one cutter tracks in each kerf. The bursting of the rock thus occurs between adjacent kerfs.

Several types of cutters are currently available: roller bits, disc cutters, and drag bits. The following paragraphs summarize the general advantages and limitations of each cutter type.

3.2.1.1 Roller Bits

Roller bits equipped with carbide buttons are usually reserved for attacking hard rock because very high contact stresses can be created due to the spherical shape of the carbide teeth fitted to the perimeter of the roller. The rock is chipped in a tangential direction, and the debris is controlled by the spacing of the teeth. As a result of the geometry of the bit and the method of attack, the debris size is small and the specific energy is high [3-5, 3-8].

3.2.1.2 Disc Cutters

Disc cutters, on the other hand, are designed to spall or burst the rock with a minimum amount of crushing beneath the edge of the disc. Discs can be designed with single or multiple cutters per cutting unit. Special carbide inserts can be added to the perimeter of the disc to deal with hard rock formations. In extremely hard rock, full face carbide inserts can be used. Disc cutters are illustrated in Figures 2-6 and 3-2.

3.2.1.3 Drag Bits

Drag bits are intended to chisel a groove or kerf and then break out the rock between kerfs. A tunnel boring machine fitted with drag

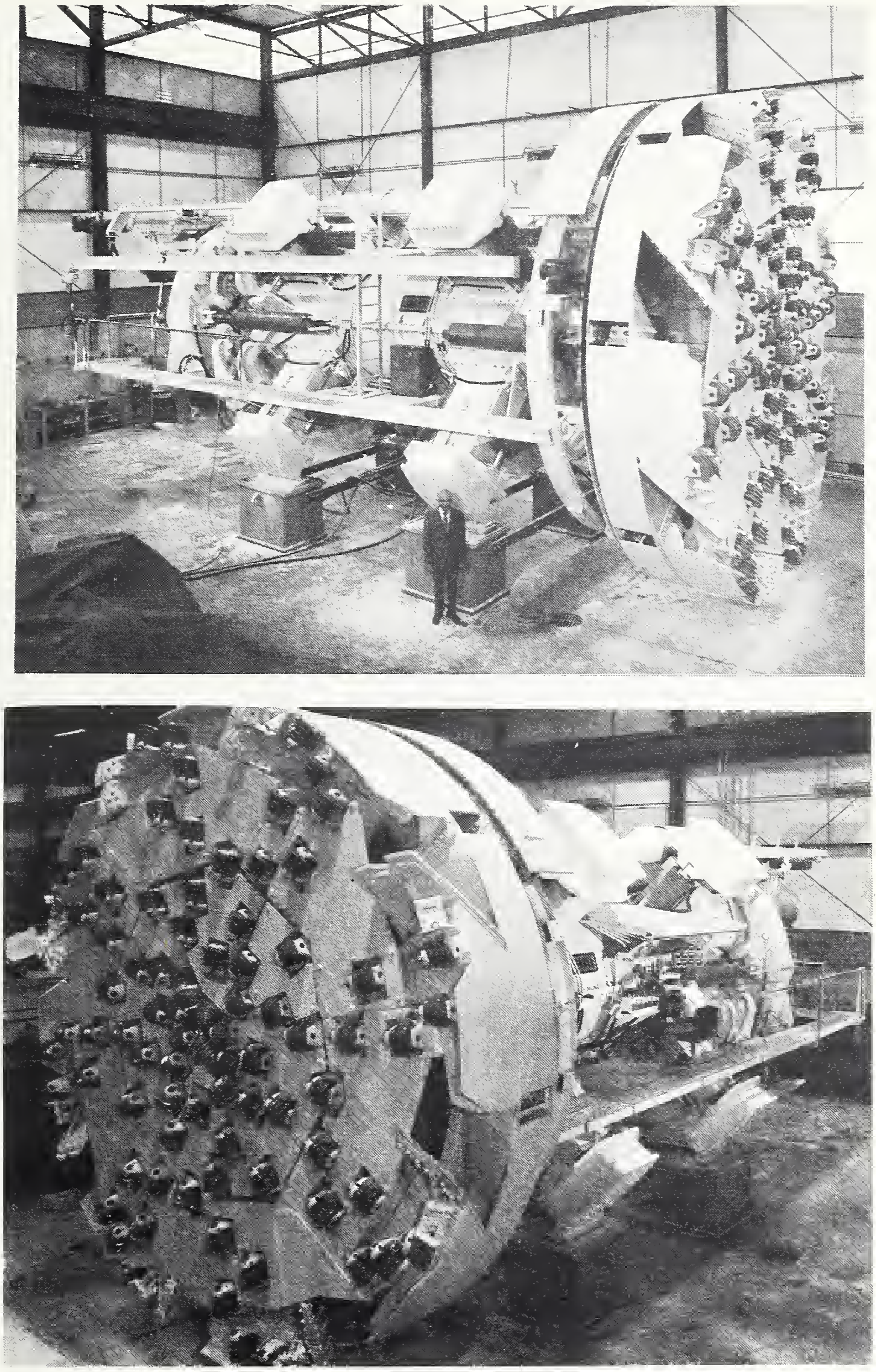


FIGURE 3-1. TWENTY-ONE FOOT DIAMETER TBM

SOURCE: JARVA

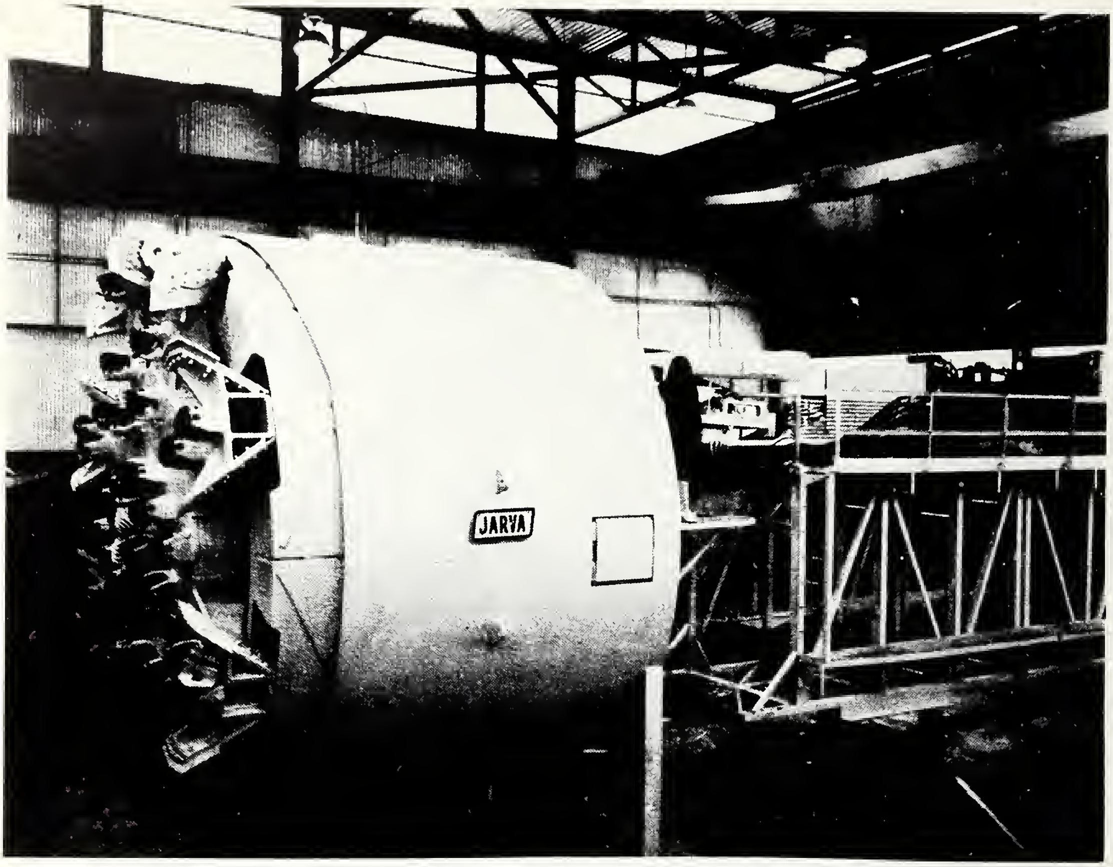


FIGURE 3-2. TBM USED FOR MIXED FACE CONDITIONS

SOURCE: JARVA

bits [3-9] was developed in England for use in the soft chalk deposits of the Channel Tunnel. Cook [3-10] analyzed rock cutter design and compared the performance of drag bits to discs. For equal rates of cutting work, Cook demonstrated that the cutting velocity of the disc must be greater than the drag bit. Since lower velocities mean longer tool life, the drag bit under favorable circumstances can be more advantageous than the roller bit.

Atlas Copco Inc. has developed a unique machine that uses drag bits to excavate rock by an undercutting process. The machine design was originally patented in 1951 by an Austrian engineer, Joseph Wholmeyer, and was later used by the German firm of Krupp as an experimental machine on soft rock deposits [3-11]. The machine is illustrated in Figure 3.3. According to the manufacturer's claims, the drill bits are in contact with only 15 to 30 percent of the total rock volume. The majority of the rock is broken off toward a free face, resulting in a coarsely fragmented muck at a relatively low specific energy [3-12]. Coarse particle size ranges from 6 to 9 in. and typically less than 10 percent of the muck is finer than 3/8 in.

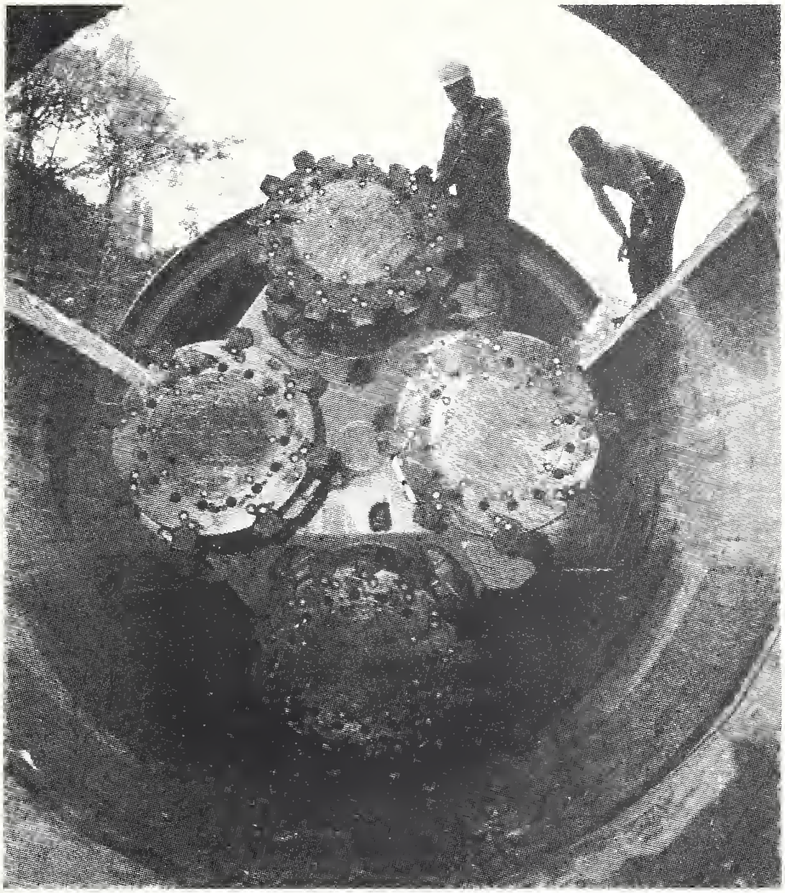


FIGURE 3-3. FULLFACE TBM

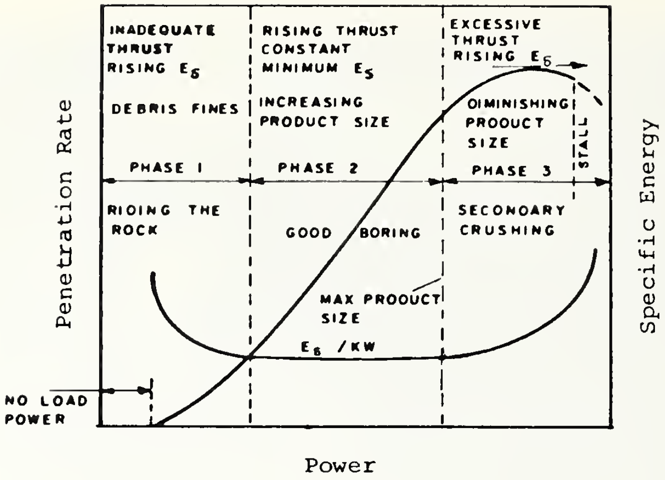
SOURCE: ATLAS COPCO

3.2.2 Thrust and Torque Capacity

The total thrust and torque required to operate a TBM efficiently is a result of several factors including the type of rock to be excavated, the number and type of cutters, the desired rate of advance, and the general hydraulic and mechanical efficiency of the TBM.

However, the overall power curve, as shown in Figure 3-4, provides some basic insight into the rock drilling process. As the machine starts to attack the rock face, the applied pressure is low and the cutters ride the rock and produce little penetration and a fine debris. As the thrust pressures are increased the cutters engage the rock and, above a critical thrust, rock fragmentation begins.

Once the rock fragmentation begins, there is a linear relationship between penetration rate and power. An increase in power results in a proportional increase in penetration rate. Also, the average size of the debris increases and "good boring" is obtained.



Note: E_s refers to specific energy

FIGURE 3-4. TYPICAL TBM POWER CURVE - PENETRATION RATE VERSUS POWER [3-8]

SOURCE: GAYE; p. 41

If the thrust is continually increased, secondary crushing becomes a factor; the penetration rate falls off and the muck particle size also decreases. Laboratory tests of single cutters have indicated similar trends [3-13].

The efficiency of the overall boring process is proportional to the reciprocal of the specific energy. As shown in Figure 3-4, the specific energy per unit of power remains constant during the good boring range of penetration. When the rock is under attack, the cutters theoretically apply equal forces on the face. If the number of cutters is increased and the force per cutter is maintained, then specific energy increases and the efficiency decreases. If the number of cutters is reduced, the spacing between cutters increases and efficiency improves.

As the spacing between cutters is increased, it becomes necessary to increase the force per cutter in order to provide an increase in the lateral force. The increase in laterial force is required to shear the additional length of rock contained between the adjacent kerfs. Therefore, for a constant force per cutter, there is an optimum cutter spacing. The spacing of disc cutters can be varied during field trials to determine the optimum spacing for a given rock type.

It should be noted that an increase in the force per cutter will also result in an increase in the depth of penetration of the cutter. Consequently, for a wedge shaped cutter, the volume of rock broken free is proportionally increased and the work per volume of rock, the specific energy, remains constant. The efficiency of the machine is thus unchanged.

During good boring the specific energy remains nearly constant. An analysis of the cutting action of disc cutters reveals that the specific energy due to thrust is small compared to that due to torque [3-8]. For a given machine with fixed cutter spacing, energy considerations lead to the conclusion that the tangential force should be proportional to the penetration per revolution during good boring. A variation in the applied torque or tangential force will therefore have a substantial effect on the penetration rate and little effect on the particle size as determined by the kerf spacing.

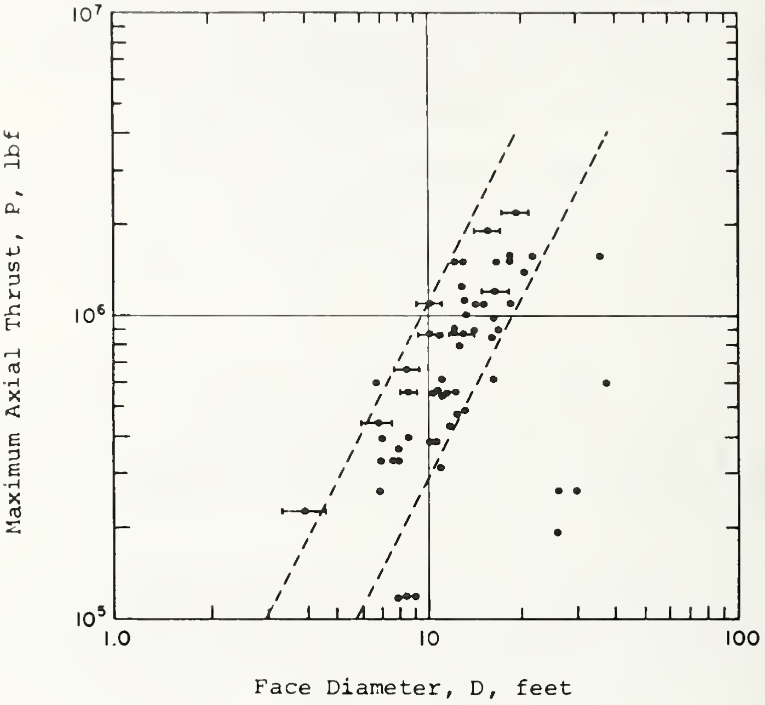
The kerf spacing must be chosen as a compromise between the maximum allowable load on the cutter bearings and the use of a close spacing which results in a small debris and a more inefficient fragmentation process. For maximum performance in a given rock, the cutters should be working at their full rated capacity at the same time that the maximum torque is generated.

Typical values of thrust and torque have been summarized by Mellor and Hawkes [3-7]. Plots of thrust and torque versus face diameter are shown in Figures 3-5 and 3-6 respectively. The thrust force per cutter was found to range from 12,000 to 52,000 lb; the typical value is approximately 30,000 lb. Average thrust pressures (thrust divided by area) on the rock face range from 25 to 100 pounds per square inch.

Data plotted in Figure 3-6 show machine torque to be proportional to the diameter raised to a power of approximately 2.3. For a constant head rotational speed, the torque should be proportional to the square of the diameter. The variation is attributed to the fact that larger machines typically rotate at slower rates, probably to reduce rotational speed of the peripheral cutters.

Horsepower data for tunneling machines are shown in Figure 3-7. Larger machines generally have lower rating of power per unit area of face.

In summary, TBM's are designed to produce the best penetration rate in a given rock by developing optimum thrust and torque forces. There is a range of input power during which good boring is developed. The muck particle size is related to the spacing of cutters. This spacing is adjusted in accordance with cutter bearing capacity to produce the optimum boring rate. The size of the muck particles is significant only if the particles are very small indicating poor fragmentation or if they are too large and can clog the cutting discs or mucking machinery.



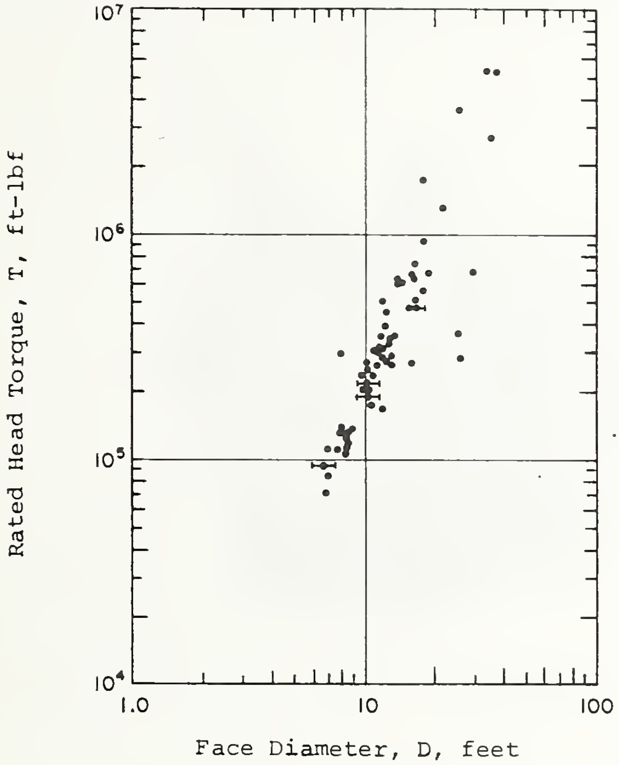
Note: $P = K_p D^2$

for typical modern machines;

$2.9 \times 10^3 < K_p < 1.1 \times 10^4$ lbf/ft^2

FIGURE 3-5. MAXIMUM AXIAL THRUST VERSUS FACE DIAMETER FOR HARD ROCK TBM's [3-7]

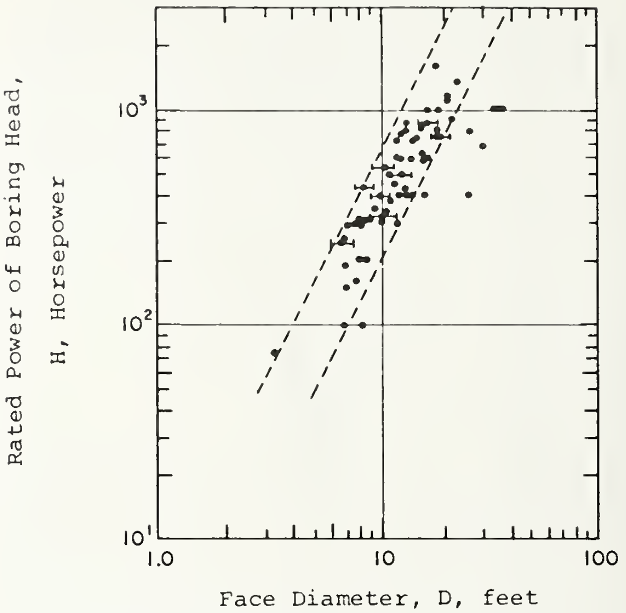
SOURCE: MELLOR & HAWKES; p. 1151



Note: $T = K_T D^{2.3}$

FIGURE 3-6. RATED HEAD TORQUE VERSUS FACE DIAMETER FOR HARD ROCK TBM's [3-7]

SOURCE: MELLOR & HAWKES; p. 1153



Note: $H = K_H D^2$

for typical modern machines:

$1.9 < K_H < 6.2$ hp/ft^2

FIGURE 3-7. RATED POWER OF BORING HEAD VERSUS FACE DIAMETER FOR HARD ROCK TBM's [3-7]

SOURCE: MELLOR & HAWKES; p. 1152

3.2.3 Typical Gradation of TBM Muck

The gradation of TBM muck will depend on the rock type, machine characteristics, and operating conditions. The larger particles are typically thin with maximum dimensions ranging from 3 to 5 in. A photograph of muck produced by a Robbins TBM from Contract A6a in the Washington DC METRO is shown in Figure 3-8. Note the sharp angular characteristics of the muck particles shown in the close-up photograph.

(a) Muck pile (3 in. to No. 200 sieve size)

(b) Close-up (2 in. size)

FIGURE 3-8. ROCK MUCK FROM WASHINGTON METRO CONTRACT A6a

Other investigators, Holmes & Narver Inc. [3-14, 3-15] and Saperstein and Raab [3-16] have collected and analyzed samples of TBM muck. Pertinent data from tunnels used in their studies have been summarized in Tables 3-1 (a and b) and 3-2. Gradation data from these reports have been reproduced in Appendix B.

A comparison of the shapes of the curves indicates little difference among the samples. For example, the maximum particle size is usually less than 5 in. and almost all samples contain less than 15 percent silt size particles (percentage is smaller than the No. 200 mesh sieve). Intermediate particle sizes generally include fine gravel and coarse to fine sand. Since all particles must pass through sieves with square openings, it should be noted that gradation curves represent the middle dimension of a "rectangular prism". Thus the typical long thin particle shape is not apparent from gradation data alone.

Nevertheless the samples would normally be classified as gravelly coarse to fine sands, trace to little silt and trace cobbles (particles 3 to 8 in.). The samples would also be described as cohesionless since little or no clay size materials are included. However, if the muck samples are damp, the muck may display "apparent cohesion." This apparent cohesion allows the muck to "ball up," but either additional water or drying will eliminate the apparent cohesive properties.

In an attempt to relate typical gradation properties to rock type, the coefficients of uniformity (C_u) and of curvature (C_c) were evaluated for the gradation curves in Appendix B. These coefficients are commonly used to evaluate whether or not a soil sample is well-graded [3-17]. A well-graded soil would have nearly equal proportions of gravel, sand, and silt sizes. For example, a soil consisting of cobbles mixed with silt would be "gap-graded" since no sand size particles were included. Generally, well-graded soils are preferred in construction activities because they are more stable when compacted. The Unified Soil Classification System has incorporated the coefficients of uniformity and curvature to aid in the description of soil types.

The coefficients describe the slope and shape of the gradation curve and are defined as follows:

$$\text{Coefficient of uniformity, } C_u = \frac{D_{60}}{D_{10}}$$

$$\text{Coefficient of curvature, } C_c = \frac{(D_{30})^2}{D_{10} \times D_{60}}$$

D_{10} = Diameter at which 10 percent of the material is finer.

D_{30} = Diameter at which 30 percent of the material is finer.

D_{60} = Diameter at which 60 percent of the material is finer.

TABLE 3-1a. BORING MACHINE TUNNELS SAMPLED BY HOLMES & NARVER, INC. [3-15]

SOURCE: HALLER; Appendix C

Sample No.	Name	Location	Rock Type	Nominal Compressive Strength q_u ksi	Diameter	Number & Type of Cutters	Machine
16	Nast Tunnel	Merideth, Colorado	Granite	18	9'-9"	25 - Carbide button	Wirth
17	Lakeshore Mine	Casa Grande, Arizona	Quartz Monzonite	32	13' (Vertical Bore)	27 - Steel Disc	Robbins H81R
18	Nast Tunnel	Merideth, Colorado	Granite	24	9'-10"	29 - Carbide Button	Wirth
19	New York City Contract #13	New York City, NY	Mica Schist	13	8'-6"	17 - Disc	Jarva 8-806
20	Name and Location Not Known		Mica Schist	11	11'	34 - Multiple Disc	Jarva, Mark 11-1100
21	Name and Location Not Known		Sandstone	22	18'-1"	47 - Steel Disc	Robbins 181-122
22	Name and Location Not Known		Limestone	20	13'-8"	28 - Carbide button, roller disc, and tricone	Alkirk
23	Name and Location Not Known		Sandstone	.05 to .15	10' (high) 8' (wide)	72 - Carbide tipped 'pick'	Alpine
24	Name and Location Not Known		Siltstone	2	20'-6"	36 - Discs 32 - Pick bits	Dresser TB-205
25	Current and Layout Tunnel	Heber City, Utah	Granite Gneiss	9	13'	19 - Carbide	Calweld Hardrock Model #40
26	Mather "B"	Negaunee, Michigan	Hematite	7	9'-11½"	278 - Drag bits	Calweld Oscillator
27	New York City Contract #13	New York City, NY	Mica Schist	15	11'	36 - Disc	Jarva, 12-1100
28	Name and Location Not Known		Limestone	36	11'-2"	27 - Triple Disc and cone	Jarva Mark 11-1100
29	Name and Location Not Known		Limestone	29	13'-8"	28 - Carbide Button, roller, disc, and tricone	Alkirk
30	Name and Location Not Known		Sandstone	22	18'-1"	47 - Steel Disc	Robbins 131-122
31	Name and Location Not Known		Sandstone	10	12'-11"	32 - Steel Disc	Robbins 141-127
32	Name and Location Not Known		Sandstone	11	18'-4"	32 - Carbide Button, roller, disc, and tricone	Lawrence HRT
33	Name and Location Not Known		Limestone	26	10'-4"	26 - Discs	Robbins 105-144
34	Nast Tunnel	Merideth, Colorado	Granite	18	9'-9"	25 - Carbide Button	Wirth
35	Lakeshore Mine	Casa Grande, Arizona	Quartz Monzonite	3	4' (Vertical Bore)	11 - Steel Disc	Robbins H81R
36	Mather "B" Mine	Negaunee, Michigan	Hematite and Martite	6	10' (Wide) x 9'-6"	68 - Carbide tipped "Plumb Bob" type	Alpine Model F-6a

TABLE 3-1b. DRILL AND BLAST TUNNELS SAMPLED BY HOLMES & NARVER, INC. [3-15]

SOURCE: HALLER; Appendix C

Sample No.	Name	Location	Rock Type	Nominal Comprehensive Strength, q_u, ksi	Tunnel Size	Number and Dimensions of Drill Holes	Drilling Machine
37	Hunter Tunnel	Merideth, Colorado	Granite Gneiss	39	10' x 10' (modified horseshoe)	36-40 holes, 1-3/4"ϕ by 11' deep	4 Boom Hydrojib Jumbo
38	Hunter Tunnel	Merideth, Colorado	Granite Gneiss	29	10' x 10' (modified horseshoe)	40 holes 1-3/4" ϕ by 11' deep	4 Boom Hydrojib Jumbo
39	Homestake Mine	Lead, South Dakota	Phyllite	19	7'6" wide by 7'6" arch	34 holes, 1¼" ϕ by 6' deep	2-6' Fixed Air Legs
40	Lakeshore Mine	Casa Grande, Arizona	Quartz Monzonite	7	15' wide by 14' high (arched back)	42 holes 1-3/4"ϕ by 10½' deep	3 Boom Hydrojib Jumbo
41	Name and Location Not Known		Sandstone	.05 to .15	5' wide by 9' high (rectangular)	18 holes, 1½" ϕ by 6' deep	LEROI Model 35
51	Lakeshore Mine	Casa Grande, Arizona	Quartz Monzonite	25	18' wide by 16' high (arched back)	47 holes 1-3/4" ϕ by 10½' deep	Gardner-Denver 3 Boom Jumbo
52	San Manual Mine	San Manual, Arizona	Quartz Monzonite	19	12' by 12'	52 holes 1-5/8" ϕ by 5' deep	3 Boom Hydrojib Jumbo
53	Lakeshore Mine	Casa Grande, Arizona	Quartzite and Tracite	26	16' wide by by 14'7" high (arched back)	42 holes 1-3/4" ϕ by 6' deep	Gardner-Denver 3 Boom Jumbo
54	Lakeshore Mine	Casa Grande, Arizona	Quartz Monzonite	28	18' wide by 16' high (arched back)	47 holes 1-3/4" ϕ by 10½' deep	Gardner-Denver 3 Boom Jumbo
55	Name and Location Not Known		Siltstone and Shale	23	24' wide by 7½' high (rectangular)	35 holes 1-3/4"ϕ by 10½' to 11' deep	2 Boom Hydrojib Jumbo
56	Magma Mine	Superior, Arizona	Conglomerate	11	9' by 10' high	42-50 holes 1-3/8" by 5½' deep	3 Boom Hydraulic Jumbo
57	Name and Location Not Known		Granite	35	10' by 10' (horseshoe)	48 holes 1-3/4"ϕ by 8' deep	Crawler Jumbo
58	Hunter Tunnel	Merideth, Colorado	Granite	32	10' by 10' (modified horseshoe)	38 holes 1-3/4"ϕ by 10½' deep	Hydrojib Jumbo
59	Nast Tunnel	Merideth, Colorado	Biotitic Granite	28	10' high by 16' wide by 8' (alcove)	72 holes 1-3/4"ϕ by 9' deep	2-SS3F

TABLE 3-2. BORING MACHINE TUNNELS SAMPLED BY SAPERSTEIN AND RAAB [3-16]

SOURCE: SAPERSTEIN & RAAB; p. 713

Sample No.	Name	Location	Rock Type	Nominal Compressive Strength, q_u, ksi	Diameter	Number & Type of Cutters	Machine
1 to 5 & 10	Navajo Irrigation, 1971, 1972	Farmington, New Mexico	Sandstone	3	11'	36 double disc	Dresser
6 & 13	White Pine, 1971, 1972	White Pine, Michigan	Sandstone Shale	25 10	18'	47 disc	Robbins
7	Moss Point Drainage System	Euclid, Ohio	Shale	2	14'3"	30 multi-disc	Jarva Mark 12-1403
8	North Branch Interceptor Sewer Conduit	New York City	Mica Schist	25	11'	25 multi-disc with button insert	Jarva Mark 12
9	Queen Lane Raw Water Conduit	Philadelphia, Pennsylvania	Mica Schist & Quartz	25	11'	27 double disc	Jarva Mark 11-1100
11	Currant Creek	Heber City, Utah	Sandstone	5	13'	29 disc	Robbins 141-1
12	Toronto Interceptor Sewer	Toronto, Canada	Shale	5	12'	25-30 disc	Robbins 126
14	Nast	Aspen, Colorado	Granite	30	10'	26 button rollers	Wirth
15	Lawrence Avenue	Chicago, Illinois	Dolomitic Limestone	20	13'8"	28 disc with button insert	Lawrence

The following criteria have been generally accepted as defining a well-graded sample:

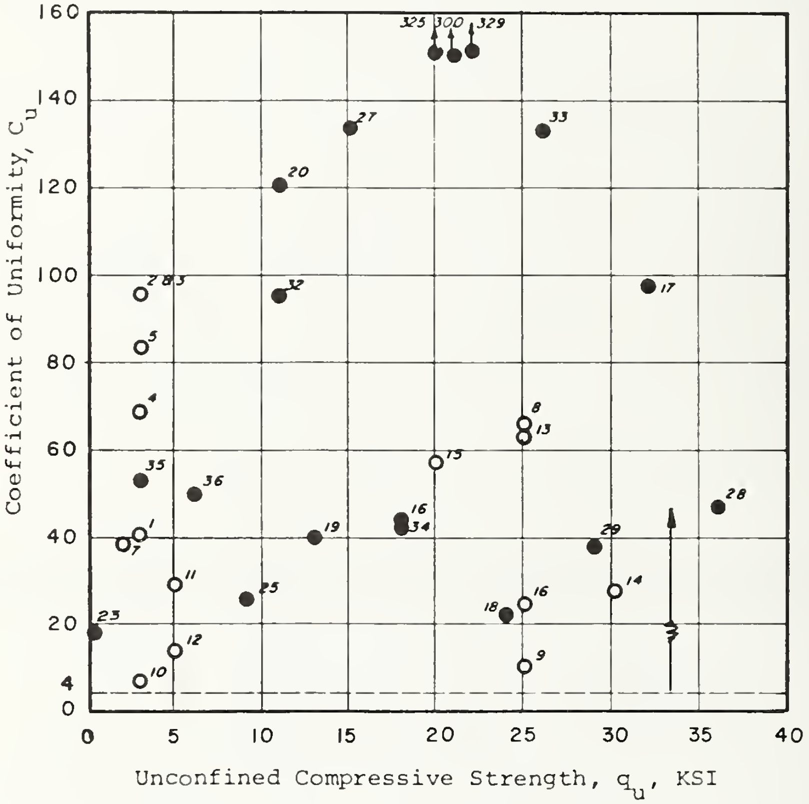
$$C_u > 4$$

and

$$1 < C_c < 3$$

These coefficients have been evaluated and plotted versus nominal unconfined compressive strength of the rock in Figures 3-9 and 3-10. Compressive strength data were not available for all samples. From these plots it is evident that, independent or rock strength, all samples met the criteria $Cu < 4$. However, not all of the samples meet the criteria $1<C_c<3$. For rock strengths less than 20 kips per square inch (ksi) the average value of C_c is approximately 1; maximum values are typically less than 2. For hard rocks with strengths greater than 20 ksi, values of C_c fall above and below the acceptable range. This accounted for, since hard rocks are commonly mined with carbide insert discs or carbide roller bits which can produce additional crushing. This crushing action can produce more fine particles resulting in proportionately lower values for D_{30}, which normally represents sand size particles. Lower values of D_{30} result in low values C_c. For example, the gradation curve for Sample No. 8 (Appendix B, Figure B-2) shows a bulge in the sand size range. On the other hand, if hard rocks are mined with disc cutters, a gradation of material representative of Sample No. 13 (Appendix B, Figure B-4), larger mid-range particles are produced. The value of D_{30} is thus increased and C_c becomes comparatively large.

Several curves, such as Sample Nos. 31, 32 and 33 (Appendix B, Figure B-10) resulted in extremely high values of both C_u and C_c. The



Notes: 1) $C_U = D_{60}/D_{10}$

2) For a well graded material $C_U > 4$

3) Legend for symbols

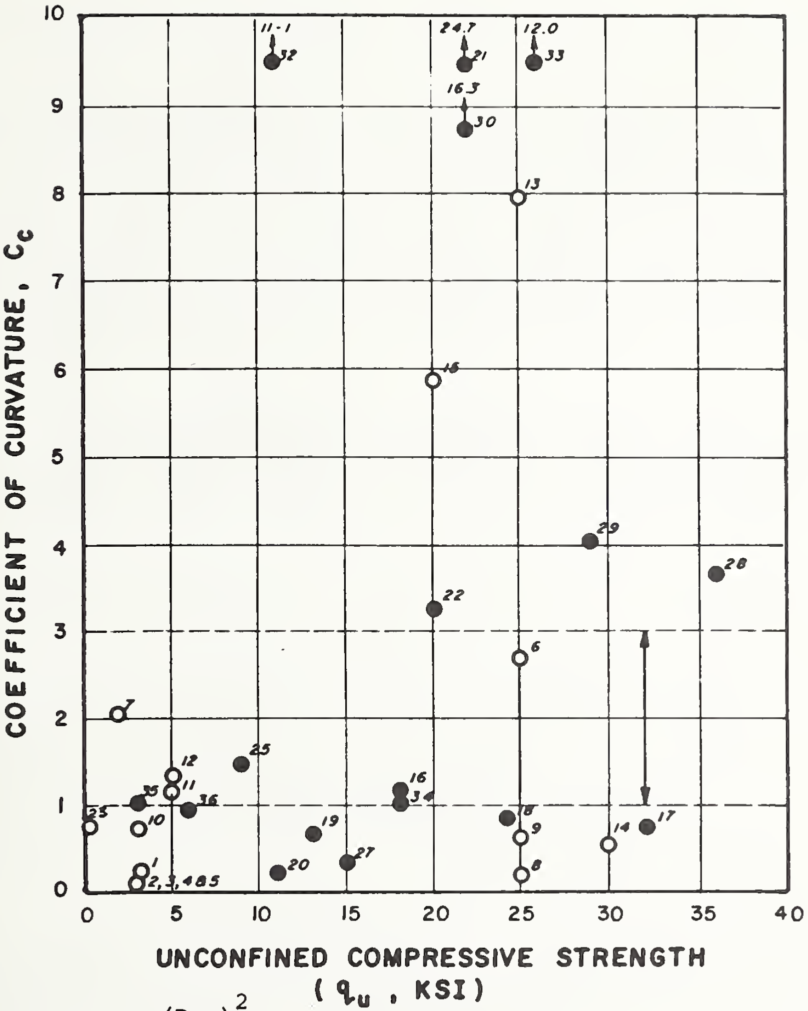
19 sample number

● researcher

○ Saperstein and Raab

● Holmes & Narver, Inc.

FIGURE 3-9. COEFFICIENT OF UNIFORMITY OF TBM MUCK VERSUS UNCONFINED COMPRESSIVE STRENGTH OF INTACT ROCK



Notes: 1) $C_C = \dfrac{(D_{30})^2}{D_{10} \times D_{60}}$

2) For a well graded material $1 < C_C < 3$

3) Legend for symbols:

25	sample number		
●	researcher	○	Saperstein and Raab
		●	Holmes & Narver, Inc.

FIGURE 3-10. COEFFICIENT OF CURVATURE OF TBM MUCK VERSUS UNCONFINED COMPRESSIVE STRENGTH OF INTACT ROCK

curve for Sample No. 31 is altogether unique and might be explained by sampling technique.

Based on an evaluation of C_u and visual inspection of gradation curves, TBM muck can be classified as a well-graded material consisting of gravel, sand, and silt size particles. Values of C_c are sensitive to interpretation of gradation curves, and use of the coefficient may be unsatisfactory, particularly for rocks with strengths greater than 20 ksi. The type of cutting bit will affect the individual particle shape and gradation. If the mining is done with discs, a larger percentage of coarse particles may be produced than if roller bits are used.

3.2.4 Effect of Variations in Thrust on Muck Gradation

Gaye [3-8] and Saperstein and Raab [3-16] have reported variations in muck gradation due to changes in the applied thrust.

In the first instance, Gaye reported data for a TBM tested at Dragonby Lines, England. Trials were conducted to evaluate machine performance in a low grade iron ore deposit.

The machine was designed with inner and outer cutting heads which rotated at 8.7 and 2.86 revolutions per minute (rpm), respectively. The inner cutting head was equipped with Hughes DGX discs and SCM roller cutters, while the outer cutting head was fitted with DGX discs. During the trial, the machine was advanced by raising the thrust pressure in increments of 100 psi and then measuring the rate of advance during a one foot stroke.

The percentage of particle sizes larger than 2 in. and smaller than one-eighth of an inch were selected by Gaye to indicate the efficiency of the drilling process. At low thrusts, the muck contained more than 40 percent of fine rock particles. As good boring developed with higher thrusts, the muck becomes coarser, and just prior to the initiation of secondary crushing, the muck contained less than 20 percent of fines and about 50 percent of rock particles were 2 in. The test data are shown in Figure 3-11.

Saperstein and Raab presented data for the muck produced at Farmington (Figure 3-9), where thrust and rotation speed were varied. These data, when prepared in plots similar to Gaye's, indicate the gradation curve changed slightly as thrust forces were decreased. A close examination indicates that the particle sizes become coarser when the thrust was decreased, Sample No. 1 compared to Sample No. 2 and 3. Secondary crushing was probably occurring at the higher thrusts. Similarly, particle sizes increased when the rate of revolution was decreased from 8 to 7 and then to 5 rpm. According to data from Raab [3-18] the operational machine thrust and rotational speeds were varied, but a thrust of 850,000 lb at 6 rpm was typical. The cutters were thus used at high thrusts and low speeds in accordance with anticipated criteria for best advance rates and longest tool life.

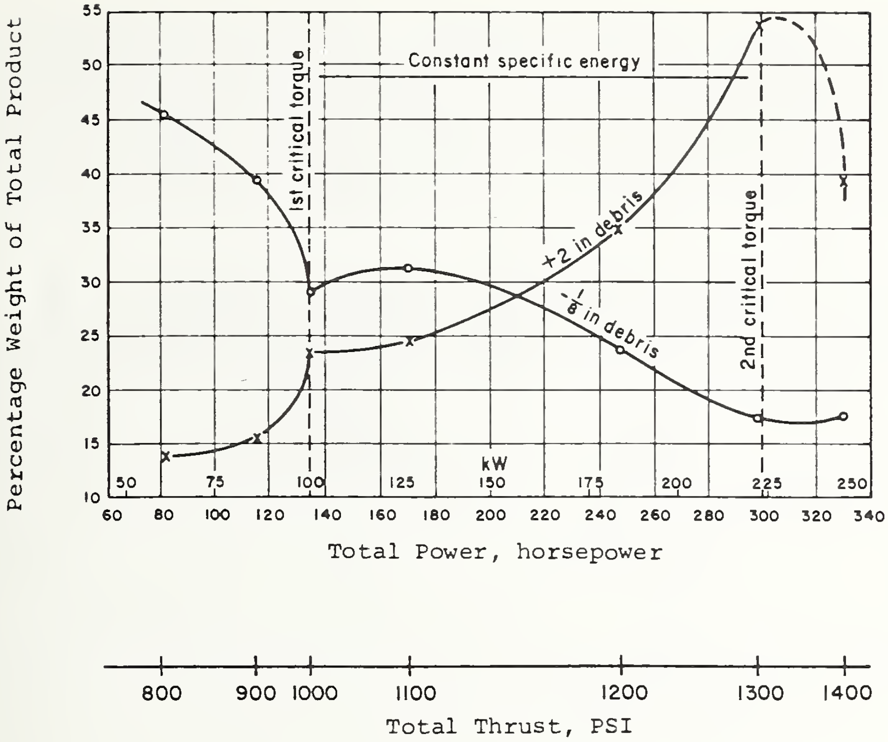


FIGURE 3-11. VARIATION IN MUCK GRADATION WITH CHANGE IN THRUST [3-8]

SOURCE: GAYE; p. 141

Thus, although thrust forces and rates of revolution may be variable on TBM equipment, it is most likely that muck of a gradation typical of the best boring conditions will be produced. Variations in thrust and speed to produce a desired gradation would result in inefficient boring and expensive tool wear.

3.2.5 Strength Properties of TBM Muck

A series of strength tests were conducted by Saperstein and Raab [3-16] on samples of TBM muck to evaluate the angle of internal friction. The raw muck samples were tested in a 3 in. diameter by 6 in. high, cylinder. Drained tests were conducted after saturating the samples with water. Several tests were conducted on samples saturated with either a detergent dust suppression agent or sodium citrate, a rock softener. Test results are presented in Table 3-3, and a plot of unconfined strength of intact rock versus angle of internal friction for TBM muck is shown in Figure 3-12.

The data in Figure 3-12 indicate, in a general sense, that the angle of internal friction is proportional to unconfined strength. Hard, sound rocks produce muck with friction angles greater than 30 degrees. Weak, friable rock, such as sandstone, or weak shales may produce muck with low friction angles. These lower friction angles are probably a result of crushing at the points of contact between particles. Shales may also react to water, swelling and breaking down into clay components. However, not all weak rocks produce low values of internal friction as evidenced by the Toronto Shale and the Farmington Sandstone where values of 21.5 and 30.0 degrees were measured.

TABLE 3-3. TRIAXIAL TEST DATA - TBM MUCK SAMPLES [3-16]

SOURCE: SAPERSTEIN & RAAB; p. 723

Tunnel Location	Rock Type	Nominal Unconfined Compressive Strength, q_u, ksi	Angle of Internal (1) Friction, 0, Degrees
Philadelphia	Mica Schist & Quartz	25	28.5
Farmington	Sandstone	3	30.0
Heber City	Sandstone	5	$0^{(1)}$
Nast	Granite	30	37.0
Chicago	Dolomitic Limestone	20	38.0
Toronto	Shale	5	21.5
While Pine (1971)	Sandstone	21	33.0

ANGLE OF INTERNAL FRICTION, ϕ, DEGREES

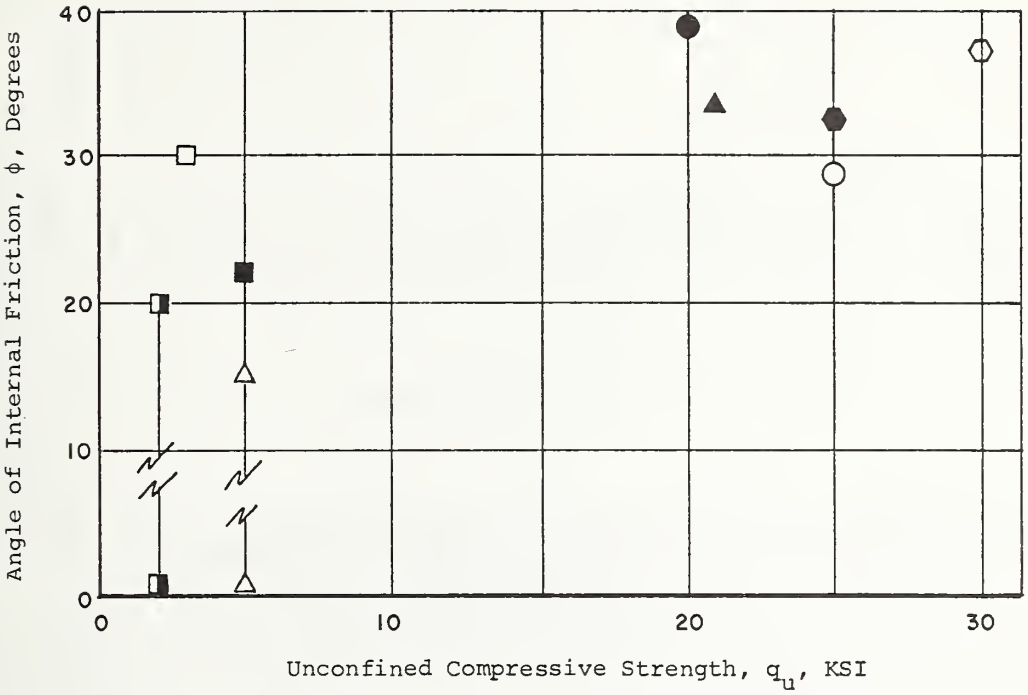
Rock Type	q_u ksi	Location	Saturation Fluids Dry	 Water	 Detergent	 Sodium Citrate
Mica Schist	25	New York	32	32	30	27
Shale	2	Cleveland	32	$0^{(3)}$	$0^{(4)}$	$0^{(4)}$

NOTES: (1) Determined from drained triaxial tests.

(2) Test data subject to interpretation; $\phi = 15^{\circ}$ is possible

(3) Test data subject to interpretation; $\phi = 20^{\circ}$ is possible

(4) Test data subject to interpretation; low values of ϕ possible



Symbol	Sample No.	Location
○	9	Philadelphia
□	1-5, 10	Farmington
△	11	Heber City
⬡	14	Nast
●	15	Chicago
■	12	Toronto
▲	6, 13	White Pine
⬢	8	New York
◨	7	Cleveland

FIGURE 3-12. UNCONFINED COMPRESSIVE STRENGTH OF INTACT ROCK VERSUS ANGLE OF INTERNAL FRICTION FOR TBM MUCK [3-16, 3-18]

SOURCE: SAPERSTEIN & RAAB

The hardness of individual grains or particles must be considered. Thus a weakly cemented sandstone consisting of hard quartz particles could produce high friction angles, particularly for well-graded samples.

The use of detergents or rock softening chemicals reduces the values of the angle of internal friction. Sound mica schist from New York showed a drop from 32 to 27 degrees when sodium citrate was added to the pore water in the triaxial sample. Softening of the rock at interparticle contact points probably accounts for the strength loss.

In summary, the angle of internal friction for well-graded TBM muck from hard rocks may range from 30 to 40 degrees. Weaker rocks may produce muck with friction angles measuring from 15 to 30 degrees depending on the nature of the rock. Detergents and rock softening chemicals can decrease measured friction angles.

3.3 ROCK EXCAVATION BY DRILLING AND BLASTING

Drilling and blasting techniques have been developed to the stage where the use of blasting agents is frequently more economical than the tunnel boring machine concept. The techniques can be adjusted and adapted easily for small and large diameter tunnels and varying types of rock hardness and competency of rock.

Advantages include flexibility of the technique and low initial cost of the operation. A contractor has a small capital outlay for the machinery needed for drilling and almost no capital investment as to the blasting agents used since the supplier is more than happy to provide storage and hauling facilities for the same price.

The disadvantages of drilling and blasting include the following: dangers of overbreak and rock damage, cyclic mining activities, and the need for large crews and skilled miners.

The primary requirement used in drilling consists of air operated, hydraulically maneuverable, drills of high strength steel to which rock boring bits containing chisel teeth of tungsten carbide or tungsten carbide buttons are attached. Drilling is performed from a platform known as the drilling jumbo, of which a variety of types exist; it could be mounted on a rubber tired vehicle; it could be a track mounted rig with folding sides, permitting maneuvering of mucking and loading equipment to the heading; or it could be a gantry rail jumbo, a drilling platform that moves on wide spaced rails, allowing the mucking and loading equipment to travel below and through the rig itself. Figure 3-13 shows a typical drill jumbo used in tunneling. The production rate of a drilled and blasted tunnel is a function of coordination between drilling, loading and mucking. Optimum progress can be achieved at minimum cost by properly balancing the drilling and leading cycle with the mucking cycle.

When rock in a tunnel is excavated by conventional drill and blast procedures, the following variables are of primary importance for determining the size characteristics of the muck.

a. Drill hole characteristics

b. Amount and type of explosive

c. Blasting pattern

d. Overall geometry

e. Rock mass characteristics

No theoretical relationship exists, however, for predicting the degree of fragmentation or the size distribution of the muck produced by a given blast as a function of the above variables. Predictions are still based almost entirely on empirical information collected by blasting experts. Moreover, the prediction of experts would only be used for cost estimates and for preliminary test blasts at the site. After test blasting, the optimum drill and blast cycle giving the best advance rate would be chosen.

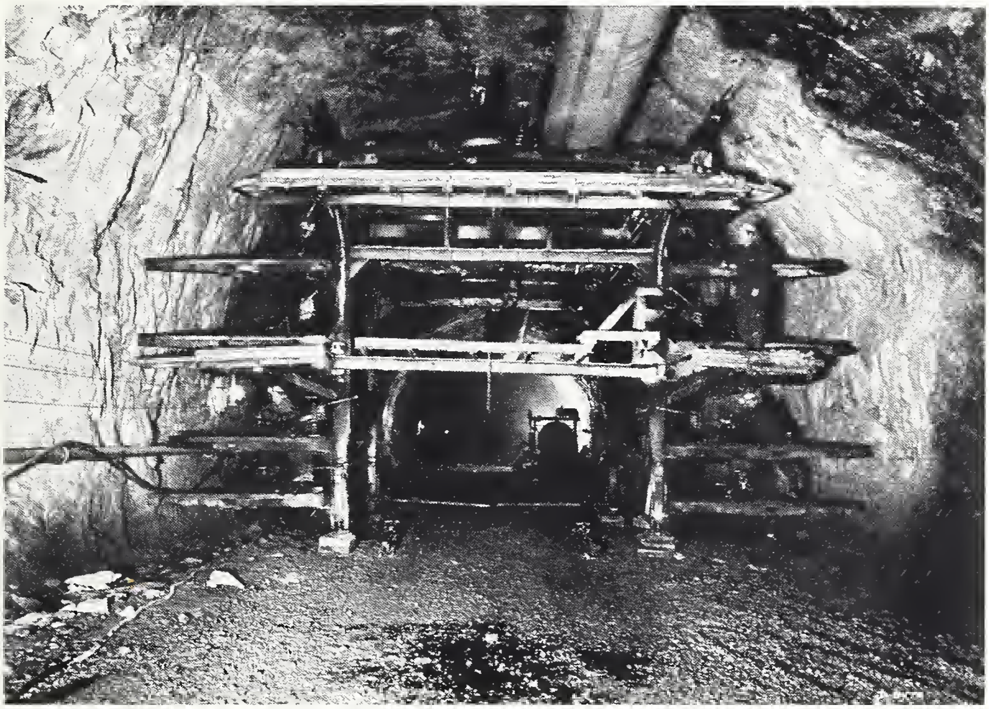


FIGURE 3-13. TYPICAL DRILL JUMBO

SOURCE: INGERSOL - RAND

The character of the muck pile is an important variable in determining the advance rate. In general, the contractor attempts to minimize the amount of drilling, explosive, overbreak and fumes and maximize the amount of fragmentation. As more holes are drilled and more explosive is used, costs and fragmentation generally increase, but costs for loading and hauling the muck decrease. Cost decreases are realized by less wear and tear on equipment, quicker handling, and fewer secondary blasts to break large blocks. Hence, an optimum size distribution of the muck minimizes the total cost of rock tunneling. Usually the optimum size distribution is determined by "feel," rather than by cost studies.

Actual fragmentation of the rock is caused by three different phenomena related to the explosion: crushing, gas pressure, and shock waves. Crushing occurs in the immediate vicinity of the drill hole and is a minor factor in fragmentation. If the rock mass does not disintegrate, very little rock is fragmented by crushing. Gas pressures contribute to rock mass disintegration by inducing separation along existing discontinuities and cracks caused by the blast. Shock waves produced by the blast do little damage until they strike a free surface. When this happens, the shock wave reflects from the free surface and induces high tensile stresses in the rock. Since rock has low tensile strenth, the reflected stress wave is very effective at causing fractures. Recent tests have shown that reflected shock waves are the most effective source of fragmentation.

3.3.1 Spacing and Number of Blast Holes

Spacing of the holes is of utmost importance. As spacing decreases fragmentation increases, but in a non-linear fashion. It rapidly becomes uneconomical to continue drilling more holes to increase fragmentation.

Hole size (diameter) is not a significant variable. But a large hole relative to the size of the charge serves to cushion the blast slightly and reduce fragmentation. The hole size can be important if the entire hole is filled with explosive since the effectiveness of the charge is related to its size. The diameter of most drill holes varies from 1-5/8 to 2 in.

Deviation of the drill hole from the intended alignment is also not an important variable unless it deviates so far that the blasting pattern is disrupted. Excessive deviation can result in excessive overbreak and increase the amount of muck.

3.3.2 Amount and Type of Explosive

The degree of fragmentation will increase in a non-linear fashion with the amount of explosive, provided the blast is well planned. The energy from the explosive can be expended in ways which are counterproductive, e.g., by increasing the throw. A scattered muck pile is difficult to load, is unsafe, and can interfere with other tunneling operations.

Many types of explosives are available, differing by their physical and chemical properties. One of the most important properties relative to fragmentation is the velocity or detonation rate of the explosive. This quantity, defined as the rate at which the detonation wave travels through a column of explosive, typically varies between 4,000 and 23,000 feet per second (fps) and depends to some extent on the diameter of the charge. As the velocity increases, the shattering effect will be greater in hard rocks although not necessarily in softer rocks. This effect also depends on the strength and density of the explosive [3-19].

The explosives used in rock tunnels are (1) explosive gels, normally refered to as stick powder, (2) an-fo, which is a mixture of ammonium nitrate and fuel oil, and (3) slurry, which is an explosive mixture in a liquid form. Recently the industry has seen the advent of a plastic explosive agent called Tovex which is contained in a fine membrane plastic tubing and is easily stored, is extremely safe to handle, and produces non-toxic fumes.

3.3.3 Blasting Pattern

The blasting pattern refers to the manner in which the explosives are detonated. It is possible to delay the detonation of specific charges relative to other charges from a few milliseconds to several seconds. This has several beneficial effects relative to fragmentation. As each blast detonates, the burden is successively reduced, facilitating disintegration and providing more free surfaces for the generation of reflected shock waves. Moreover, later blasts throw blocks of rock against rock already in flight to cause additional shattering.

The proper choice and distribution of delays is critical to a well planned blast. The failure of even a single charge in the sequence can sometimes cause the blast to fail completely. Although any reasonable delay pattern is usually better than simultaneous ignition, conclusive evidence shows that the shorter delays (millisecond) cause considerably more fracturing than the longer delays (multi-second).

3.3.4 Overall Geometry

Overall geometry refers to the spacing and depth of the holes relative to the size of the tunnel. Since spacing of drill holes has already been discussed, this section deals with the depths of the holes or the length of the round which is referred to as the burden. For small openings especially, the burden must be carefully selected to make the blast efficient [3-20]. If the burden is too great, much less rock is moved than was drilled, and the fragmentation is poor. If the burden is too small, the quantity of rock is small, the fly rock is excessive, and the fragmentation may again be poor, since the rock is simply dislodged without being fractured.

3.3.5 Rock Mass Characteristics

Each blasting job differs with respect to the rock type and the character and intensity of the natural discontinuities. Hard rock such as granite can resist the shock waves and will form large angular blocks of rock. On the other hand, sedimentary rocks, unless they are soft, fracture much more easily and absorb the blasting by crushing.

Even with the advent of smooth wall blasting and controlled detonation of the round in the tunnel, overbreak can be minimized, but never eliminated, by the use of blasting. The energy generated by explosive agents must find avenues of escape in the rock itself, and there is no method yet devised that would limit this to zero. Also the rock quality, as affected by the presence of shears and faults and the depth of the rock, play a major role in the control of overexcavation. Since blocks tend to be jarred loose by explosive forces, even smooth wall blasting has its limits in controlling overbreak in sharply dipping rock, sheared rock, and gouged areas.

The excavation cycle in a rock tunnel includes the following activities:

a. Drilling

b. Loading the charges and detonating the round; often called "load and shoot"

c. Ventilating (i.e. clear the heading of all toxic fumes)

d. Mucking cycle

e. Constructing temporary or permanent support

f. Moving equipment in and out of the heading for these various cycles

3.3.6 Typical Tunnel Blast Round

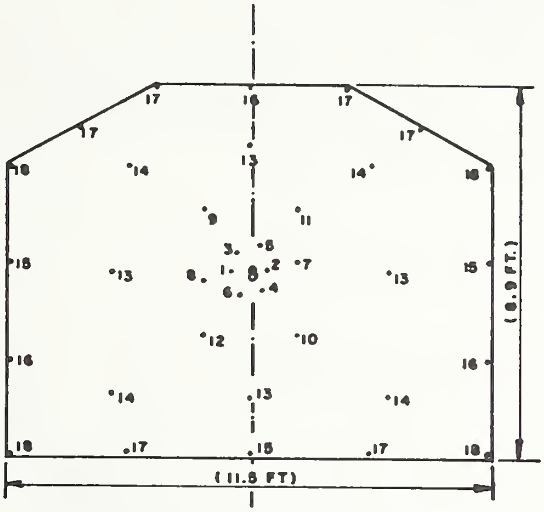
Figure 3-14 illustrates a typical tunnel blast round. The two holes in the center are oversize and not loaded which, together with the first 8 drill holes, form what is called the burn cut. Rock in this area is crushed, sheared and fractured to a large degree and blown out of the rock mass to provide relief for the rest of the blast. The remaining explosive is detonated in the order shown by the numbers at each hole. For the example sited, the first eight delays in this round were millisecond delays (nominally 0.025 second intervals), and the rest were longer delays of up to approximately 5 seconds. Fragmentation could have been improved by using all millisecond delays.

3.3.7 Typical Properties of Blast Rock

The muck generated by drill and blast mining contains particles ranging in size from cobbles and boulders to silt size particles. Properties of the rock mass can greatly affect the size of the larger particles from a given blast, whereas the crushing or pulverizing of the rock immediately around the drill hole creates fine particles.

Sound rock masses with few joints tend to generate well graded muck with reproducible gradation from each blast. On the other hand jointed or folded rock masses can produce large boulders which require secondary drilling and blasting.

SOURCE: LANGEFORS & KIHLSTRON; p. 211



Pertinent Blast Round Data

Average Hole Spacing = 2.5 feet

Total Number of Holes= 36 + 2 empty

Length of Holes = 12.5 feet

Volume of Muck = 47 cubic yards

Drill Factor = $10.5 \frac{\text{feet}}{\text{cubic yard}}$

Power Factor = $3.75 \frac{\text{feet}}{\text{cubic yard}}$

Diameter of Drill Hole = 1.4 in.

FIGURE 3-14. TYPICAL TUNNEL BLAST ROUND [3-21]

The diameter of the crushed rock zone around a drill hole increases with drill hole diameter and thus with charge concentration. Data from the Swedish Blasting Technique [3-22] are reproduced below:

Drill hole diameter mm	Concentration of charge kg/m	Crushed circular section mm
30	0.9	35
50	2.5	70
100	10.0	150

The figures in the table above are based on a high strength rock. In weaker types of rock, the amount of crushing which occurs is much greater. A larger section outside the drill hole than that shown in the table is crushed but not completely pulverized.

Muck gradation curves for several rock tunnels mined by drill and blast methods are shown in Appendix B (Figure B-12). The dimensions of cobble size pieces were not provided, but it is probable they measured several feet in longest dimension. The gradation curves for metamorphic and igneous rocks with low to high strength are similar. Note, however, that the very weak sandstone was broken down into the basic sand size particles, as would be expected by the crushing phenomenon.

Subsequent sections provide additional discussion of the strength and compression properties.

3.3.8 Fragmentation Changes - Economic Considerations

The drill and blast cycle is tailored, by trial and error, to produce an optimum advance rate. The depth of the round, drill hole spacing, and charges will be selected to minimize overbreak, the need for secondary blasting of boulders, and mucking out costs. Any attempt to change the gradation of the muck pile would probably result in additional costs and less efficient mining. Since each tunneling situation is controlled by different cost factors, including initial capital equipment outlays and normal mining costs, the additional cost would have to be determined on the basis of a thorough analysis [3-23, 3-24]. However, the following simplified example indicates that modification of the optimum fragmentation cycle may not result in a net increase in tunnel costs.

Assume for example, that a finer muck gradation is desired. Assume further that the additional drill holes, powder, caps, mucking costs and loss in rate of advance could add 3 percent to the cost of mining the tunnel. The cost for a large diameter unlined tunnel will depend on location, labor rates, rock type, etc., but could easily range from $800 to $1000 per foot. For a round producing 100 cu yd of loose muck the additional cost would amount to approximately $3.00 per cu yd. If the muck were then sold at typical market prices ranging from $3.00 to $4.00 per cu yd (for use as rockfill or a source of aggregate) the costs of deviation from the optimum blast cycle would be recovered with a potential for profit besides. The incentive for adopting a change in the fragmentation pattern could be a profit for the contractor for producing a useful raw material which could be used by the owner.

3.4 SOFT GROUND TUNNELING METHODS

Tunneling in soft ground has inherent advantages as well as disadvantages depending on the types of soils encountered. Stiff clays and hardpan or decomposed rock tend to minimize the disadvantages and the support problems. On the other hand, silty clay, clayey silt, sand, gravel and certain very plastic clays are major sources of soft ground tunneling problems. The water inflow into a soft ground tunnel, if not reduced by the use of compressed air, slurries, or other methods, tends to compound the disadvantages of soft ground tunneling. Shields are utilized to provide temporary support of the face and the forward section of the tunnel prior to erecting the primary support system or tunnel liner. Typical soft ground shields are illustrated in Figures 2-2 and 3-15.

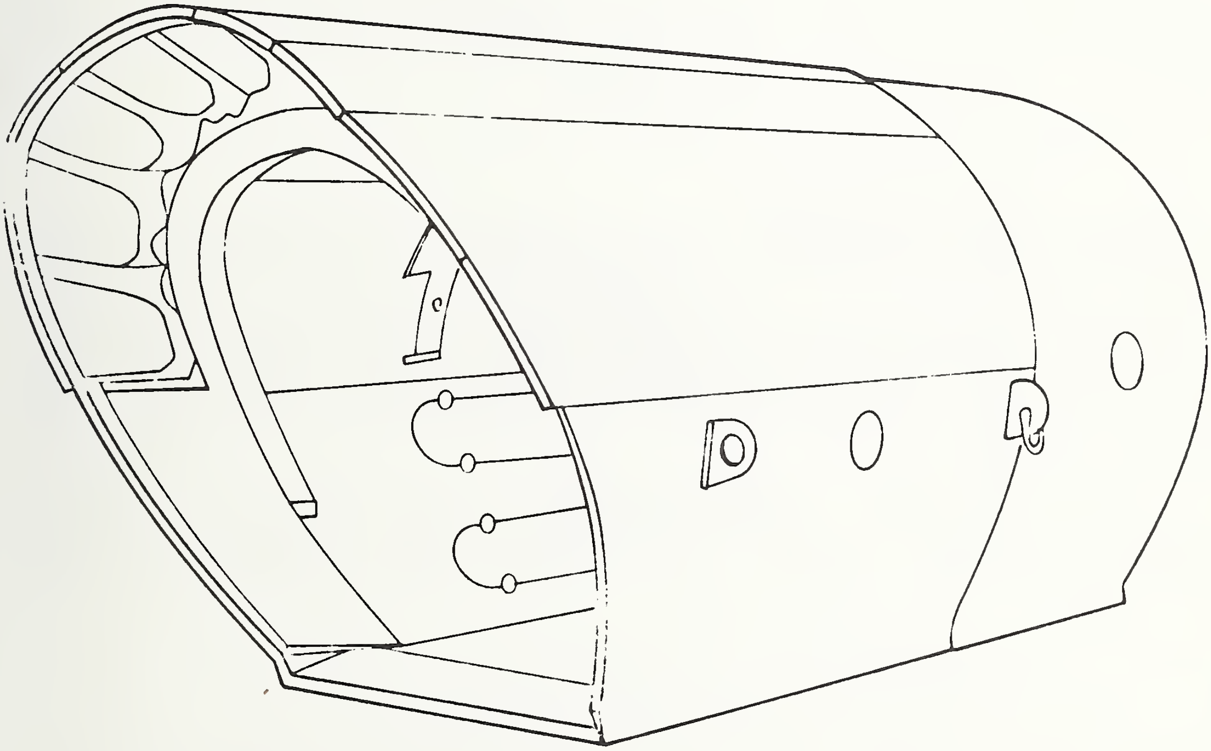


FIGURE 3-15. TYPICAL SOFT GROUND SHIELD

SOURCE: MILWAUKEE

3.4.1 Hand Mining Shields

Hand mining shields permit direct access to the face and permit miners to excavate the exposed soil using hand tools such as shovels, clay spades, and winch activated clay knives. Open face shields are used in competent ground (the soil at the face is self supporting) or else in conjunction with compressed air. Compressed air will stabilize soft soils or reduce the inflow of water at the face.

The shield consists of a steel cylinder which is forced ahead into the soil by hydraulic jacks reacting against the primary lining. A hood projects forward at the crown, providing additional support. In soft running ground, breasting plates may be erected to provide additional support.

The shield itself has no direct influence on the muck characteristics. The excavating tools can affect the general shape of the particles. For example, a clay spade (pneumatic jackhammer) in stiff clay will produce small chunks of clay.

3.4.2 Mechanical Shields

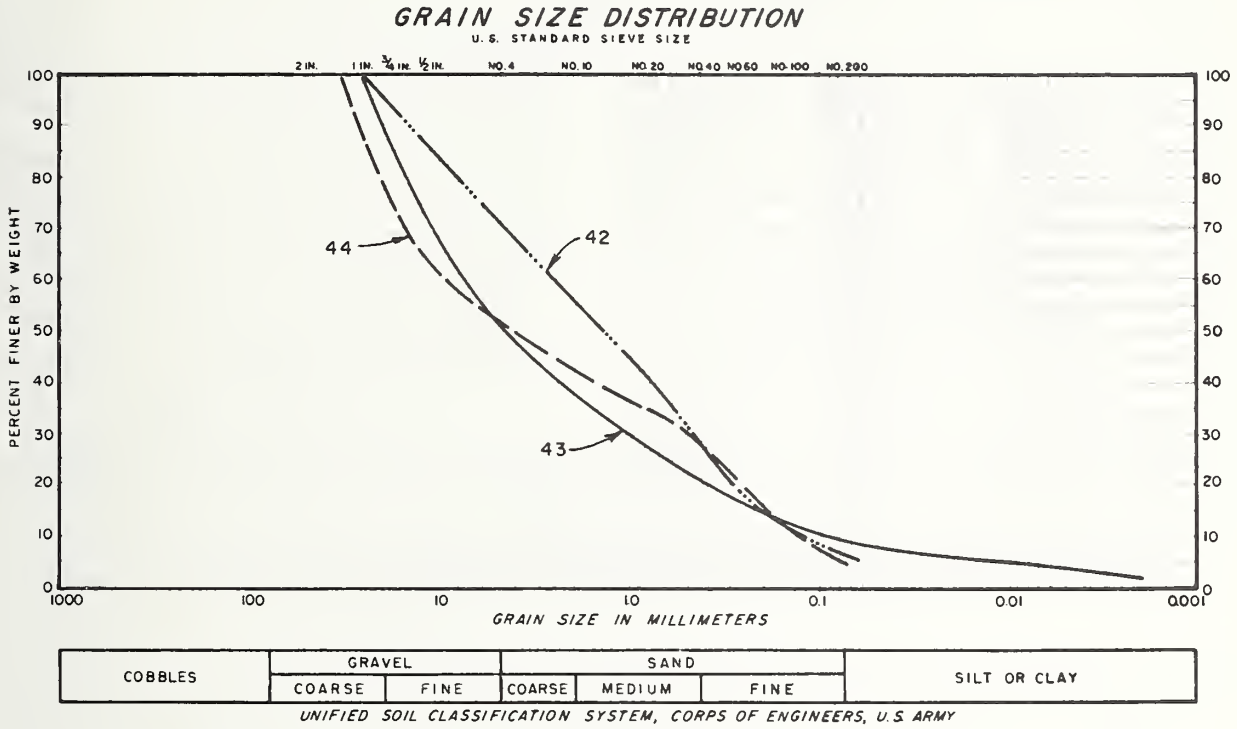
A mechanical shield is similar to a hand mining shield, with the exception that it is fitted with mechanical excavating equipment. The equipment can consist of rotary cutting wheels, an excavating "tooth" (Figure 2-2), or a hydraulically operated bucket, similar to a backhoe. The mechanical equipment permits more rapid excavation rates but also restricts access to the face. The machines are best suited for excavating stiff clays or decomposed rock where the face will stand up. Compressed air can also be used to overcome face stability problems.

The type of muck generated depends on the particular excavating equipment. A cutter shield will produce small chips (about 1 in. long) of stiff clay whereas an excavation tooth or bucket will produce larger (1 ft) clumps of soil.

3.4.3 Typical Properties of Soft Ground Muck

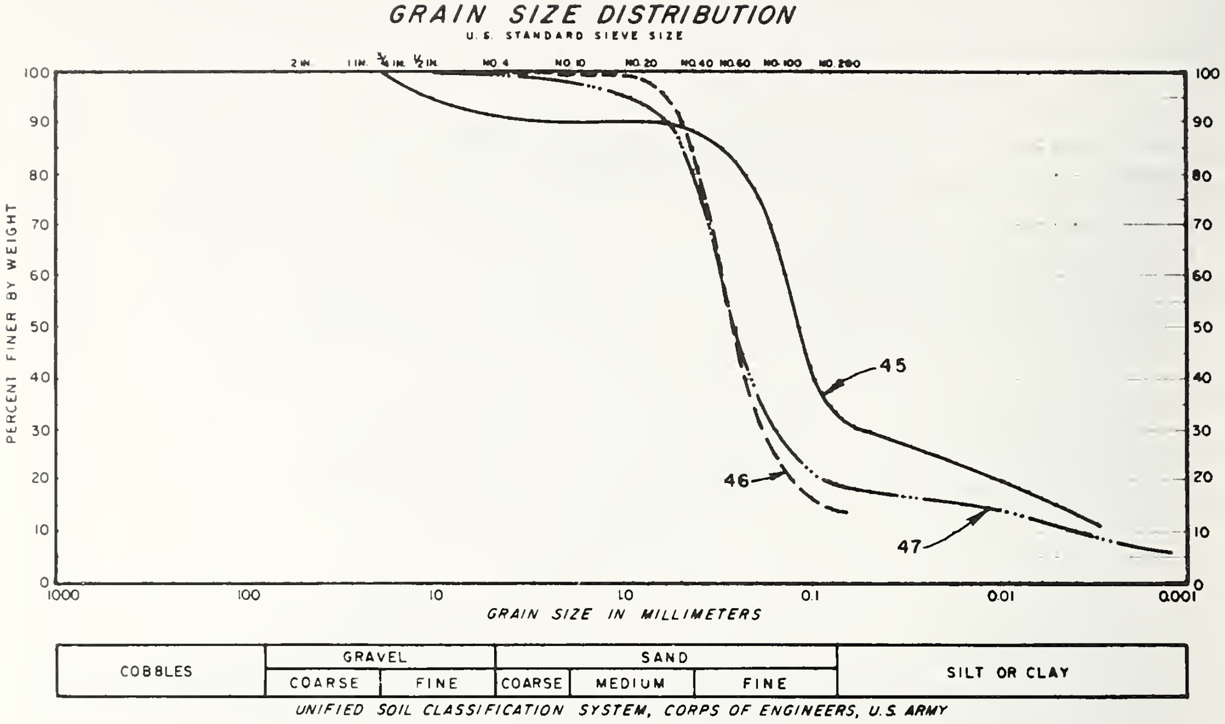
The muck produced in soft ground tunneling normally consists of chunks of soil grading into the finer individual soil particles. Cobbles and boulders will easily separate from sand and gravel deposits, but the cohesive properties of clay soils or the apparent cohesion in damp sand results in the chunky appearance of a muck pile. If the soils were allowed to dry, then the non-cohesive soils would break down into the gravel and sand components, while clayey and silty soils would dry into brick-like pieces, the harder pieces resulting from higher clay content.

Gradation curves for soft ground muck are shown in Figures 3-16, 3-17 and 3-18. The gradation of the muck will depend on the soil deposits encountered along the tunnel route. The particular type of excavating equipment will not usually affect the gradation of the muck. Additional discussion of the properties of soft ground muck is contained in Section 4.



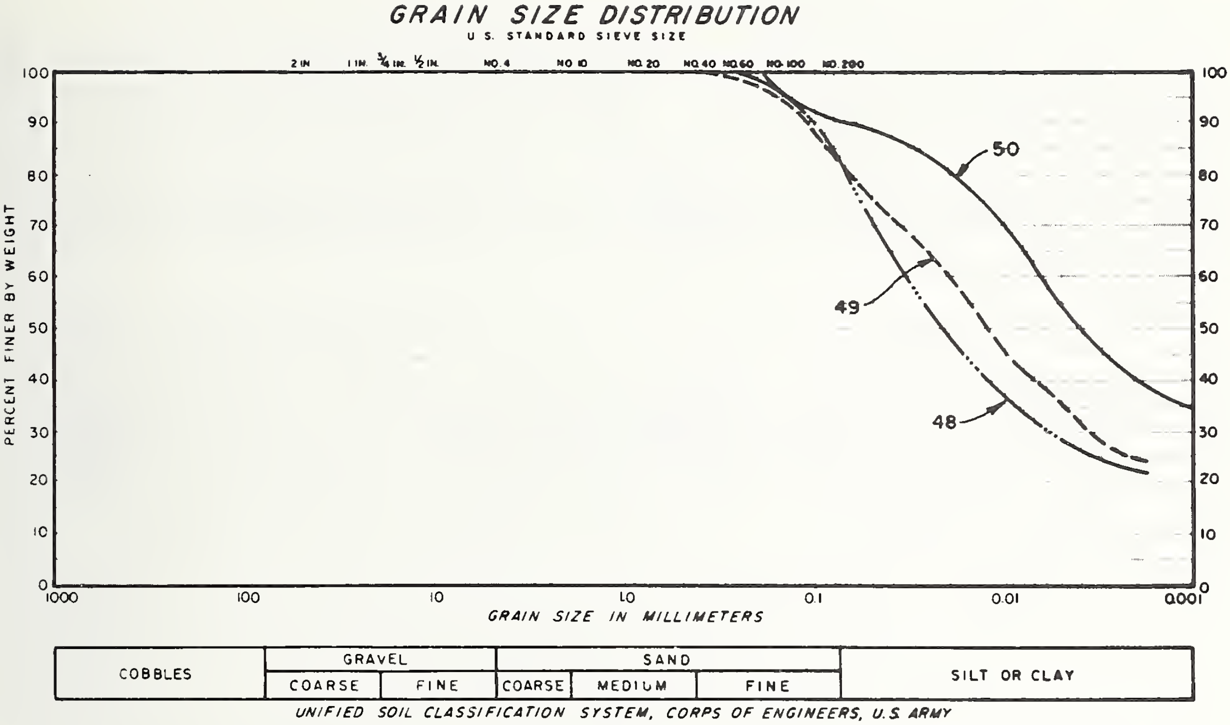
Sample No.	Description	Coefficient of Uniformity, C_U	Coefficient of Curvature, C_C
42	gravelly coarse to fine SAND	21	0.7
43	gravelly coarse to fine SAND	82	1.5
44	gravelly coarse to fine SAND	76	0.2

FIGURE 3-16. GRADATION CURVES - SAND AND GRAVEL MUCK



Sample No.	Description	Coefficient of Uniformity, C_U	Coefficient of Curvature, C_C
45	silty fine SAND, trace gravel	65	11.6
46	fine SAND, little silt, trace medium sand	30	12.0
47	fine SAND, little silt, little medium sand	75	16.3

FIGURE 3-17. GRADATION CURVES - FINE SAND MUCK



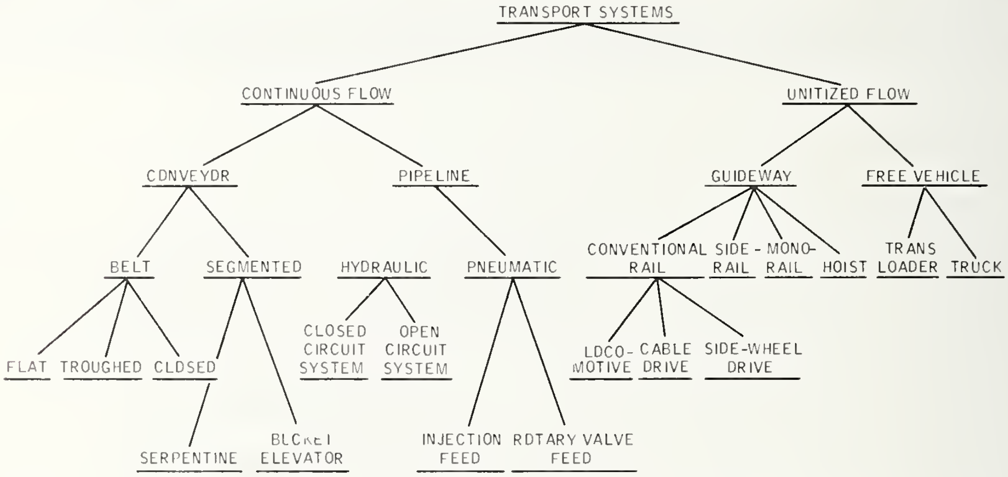
Sample No.	Description	Coefficient of Uniformity, C_U	Coefficient of Curvature, C_C
48	clayey SILT	does not apply	
49	clayey SILT	does not apply	
50	silty CLAY	does not apply	

FIGURE 3-18. GRADATION CURVES - SILT AND CLAY MUCK

3.5 MUCK HANDLING AND DISPOSAL

A significant part of the tunneling process involves the removal of muck from the tunnel face to a disposal destination. Any slowdown in this process can drastically affect the overall tunnel advance rate and may even cause a stoppage of work. It is therefore important to have a smoothly operating and efficient muck handling system. The system must be adaptable to transporting all sizes and consistencies of materials and possibly include the transportation of men and materials to the tunnel face.

Muck transportation systems can be divided into two major categories: continuous flow and unitized flow. Figure 3-19 shows how various equipment types fit into each category. Continuous flow systems are characteristic of an uninterrupted flow of material. Typically, a closed loop set-up is employed whereby the muck is continuously added and removed from the loading and destination points, respectively. The unitized system consists of discrete mechanical units which travel singly or are linked together to form a train.



SOURCE: DUNCAN; p. 2-10

FIGURE 3-19 MUCK TRANSPORT SYSTEM [3-25]

Muck characteristics can affect the choice of a particular mode of muck transportation equipment. Standard transportation equipment, however, has little effect on the properties of the muck. For example, the gradation of TBM muck is not changed during the handling process from the face to the portal. Water may drain from coarse muck such as drill and blast rock, but the basic muck constituents are unaffected by handling.

Pneumatic or hydraulic pipeline systems, however, require sorting or crushing to reduce muck particles to the maximum size compatible with the system. Table 3-4 summarizes some of the more significant muck characteristics to be considered in the selection process.

The following paragraphs describe some of the commonly used muck handling equipment and the significant muck characteristics relevant to the operation of that particular system.

3.5.1 Conveyor Systems

Conveyor systems consist of either a conveyor belt or a segmented belt. The basic parts include a drive unit and a transport medium. The drive unit provides the motive power to the entire unit, and the transport medium carries the muck from the tunnel face.

Transport mediums for the conveyor belt systems consist of continuous belts, a continuous series of metal pans or flights suported on chains, or a continuous belt fully enclosed and supported on rollers. The troughed-belt conveyor is the conveyor used most often for transporting muck. This conveyor, commonly used with TBM's, can operate at speeds compatible with tunnel advance rates.

The capacity of a conveyor belt system depends on belt speed, belt width, troughing angle (troughed conveyor belt only), and the density and angle of repose of the muck. Conveyor belt systems are very flexible and can easily be adapted to any tunnel size. Muck size is generally limited to one-fourth of the belt width [3-25]. Excessive moisture contents do not permit piling the muck high, particularly on flat type conveyor belts. In some instances the transport medium might be constructed with a screened bottom to allow drainage.

Belt conveyors are expensive, approximately $100/ft, to run the entire tunnel length [3-26]. They are used to remove muck from the tunnel face to a loading point behind the excavation work where other forms of muck handling equipment such as rail systems can then be employed. These short conveyor belt distances may be 80 to 100 ft long.

Some of the advantages and disadvantages of the conveyor belt system are listed below [3-25].

Advantages:

a. Capable of handling excavated material at any rate of heading advance

b. Compatible with most excavating and loading methods

c. Adaptable to nearly all tunnel sizes

TABLE 3-4. LIMITATIONS ON PHYSICAL CHARACTERISTICS OF MUCK FOR VARIOUS TRANSPORTATION MODES [3-25]

SOURCE: DUNCAN; p. 2-22

		Physical Characteristics of Muck					
	Mode of Transport	Block Size	Moisture	Stickiness	Density[c]	Heat and Miscellaneous Factors	Shape[d]
Continuous	Conveyors	To one-fourth belt width.	Will drain off in transit.	Will load belt excessively.[b]	Tonnage increases with higher density.	May require special belts. 200°F+. Incompatible.	All.
	Hydraulic	Need 50% 0.002 inch. May be large block limits.	Presence favors system.	Implies moisture OK.	High density increases tonnage and critical velocity.	Probably OK. Steam may be generated.	Flakey materials favored.
	Pneumatic	Works better with small material size.	Dry material better. Some moisture OK.	Cannot handle sticky material.[b]	High density increases tonnage and critical velocity.	May require insulation.	Flaky materials favored.
Unitized	Conventional Rail	All.	High content may affect rail ballast.	OK, but may require shaker for unloading.	Tonnage increases with density.	May require insulation.	All.
	Siderail	Limited by module size: 6 inches OK.[a]	Will drain in inverted position. Special electrical features required.	Difficult to unload.	Tonnage increases with density.	May require insulation.	All.
	Monorail	Limited by module size; 6 inches OK.[a]	Will drain off in transit.	Difficult to unload.	Tonnage increases with density.	May require insulation.	All.
	Hoist	All.	Will drain off in transit.	May require special unloading feature.	Tonnage increases with density.	May require insulation.	All.
	Free Vehicle	All.	High content will affect road requirements.	May require special unloading feature.	Tonnage increases with density.	May require insulation.	All.

(a) Blocks in excess of 6 inches may require crushing.
(b) Sticky materials incompatible with conveyors and pneumatic systems.
(c) Density not a critical factor due to low percentage of very light or very heavy rock.
(d) Muck shape a minor factor.

d. Small clearance requirements

e. Excellent reliability and low maintenance

f. Continuous operation

Disadvantages:

a. Does not satisfy entire materials handling need

b. Maximum particle size limited

c. Structural support system required

d. Complicated heading extension system

e. Not compatible with extremes in tunnel alignment curvature

f. Breakdown of one part shuts down entire system

Limitations:

a. Practical limit of 18 to 20 degree slope

b. Maximum particle size of 12-18 in. depending on belt width

3.5.2 Pipelines

Pipeline systems can be divided into two main categories: hydraulic and pneumatic. Hydraulic systems rely on a fluid, usually water or a slurry of fines, as the transport medium, while pneumatic systems use air. Recently published research has proposed a pneumatichydraulic system [3-27]. It is anticipated that this latter type of system could only be used to transport a uniform, small size of muck, having a maximum particle size of about 2 or 3 in.

3.5.2.1 Hydraulic

The operation of a hydraulic pipeline system consists of mixing the excavated material with a liquid, such as water, to form a slurry mix. This mix can then be pumped either horizontally or vertically through a pipeline system to a disposal point at ground surface. The pipeline system must be maintained under pressure to permit adequate particle velocity. In many instances, the transport medium (i.e. liquid) is recirculated once it has been separated from the excavated material.

Two basic systems are commonly used to transport the solids hydraulically. One system referred to as "through the pump" involves mixing the liquid and solids together and feeding the resulting slurry mix directly into a pump. A second system consists of passing only the liquid through the pump and "injecting" the solids directly into the pipeline system. This approach is called the lock-hopper system. The length of pipeline and the type of material are the primary factors governing the selection of a system [3-25].

The economic operation of hydraulic pipeline systems depends on three factors: (1) sufficient water supply, (2) high percentage of fines in the muck, and (3) a specified maximum size. In areas where water is at a premium, the used water can be reclaimed at the discharge point. This involves the additional equipment of settling tanks, pumps, filters, and water storage tanks.

Typically, 50 percent of the excavated material should pass the No. 200 mesh sieve. A crushing operation may be required ahead of the slurry operation to reduce the excavated material to a satisfactory size. Two alternatives are available when the percentage of fines is not high enough: (1) fine material can be recirculated in the system or (2) a drilling mud can be employed. The maximum size particles are usually controlled by the pump capacities available and by the size of the pipeline system. As a general rule of thumb, the pipeline diameter should be three times the maximum particle size.

Typically, a hydraulic pipeline system can pump 20 percent solids. This means that for a muck specific gravity of 2.6, the slurry mix will contain 11 parts liquid to 1 part solid, or 12 cu yd of slurry must be pumped for every cu yd of muck [3-26].

The following lists some of the primary advantages and disadvantages of the hydraulic pipeline system [3-25].

Advantages:

a. High capacities available

b. Occupies minimum of tunnel space

c. Can operate continuously

Disadvantages:

a. Does not satisfy entire material handling need

b. Requires materials processing at heading

c. Has complicated heading extension system

d. Reliability and maintenance are questionable

e. Requires high power

f. Requires large volumes of water at heading

g. Generally requires complicated solids injection system

3.5.2.2 Pneumatic

The basic component of a pneumatic air system consists of an air source such as a blower. Muck is fed through the air source into the pipeline system and directed towards its final destination point. The use of pneumatic systems over long distances (i.e. greater than 1000 ft) has been limited in present tunneling operations. A system was used with limited success in Edmonton, Canada [3-28, 3-29].

Three-inch rock has been transported at a rate of 300 tons per hour over a maximum distance of 1000 ft. It is anticipated that future research will permit the transporting of 6 to 8 in. size material over distances of 3,000 to 4,000 ft. This breakthrough would greatly eliminate the use of crushers now needed to reduce rock size to 3 in.

At the present state of the art, pneumatic pipeline systems are not considered economical or efficient since power consumption is very high. As a general rule, approximately 14 hp are needed to transport one ton of material per mile per hour. Also the steel pipes wear out from abrasion, particularly at bends.

3.5.3 Conventional Rail Systems

Conventional rail systems consist of cars or other forms of transport modules mounted on wheels, in single or linked together fashion, which ride along a track system. For transit tunnels, track systems can be single track layouts with adjacent connecting passing sidings. This set-up permits one train to wait on the siding while another train passes on the track.

The components of a conventional rail system consist of (1) individual modules (or cars), (2) propulsion mechanism, (3) track system, and (4) auxiliary loading equipment. Many different features can be incorporated into design of the individual cars. For example, unloading of the cars can be accomplished by side or bottom dumping. Diesel and battery power locomotives are used with battery driven locomotives reserved for use on short haul tunnels. Auxiliary loading equipment such as conveyor belts and Conway muckers are normally used to load the cars.

It is anticipated that rail systems will remain the most popular muck transport system for years to come for at least two practical reasons. First, most contractors have rail equipment available from previous jobs, and second, the system can keep pace with the current state-of-the-art TBM's and mechanical excavators. The system also has a dependable field performance record.

The following is a list of advantages and disadvantages of the conventional rail systems [3-25].

Advantages:

a. Easily maintained traffic way

b. Compatible with most loading systems

c. Adaptable to most tunnel sizes

d. Several power sources available

e. Satisfies entire material handling need

f. Permits relatively tight clearance limits

g. Transports construction equipment and personnel

Disadvantages:

a. Passing locations are fixed or semi-movable

b. Derailment shuts down entire system

c. Unloading points relatively fixed

d. Track may complicate concreting operations

3.5.4 Rubber-tired Haulage

This category of muck haulage systems refers to those vehicles which can move about without the use of guideways. There are two basic groups of equipment: transloaders and trucks (or hauler). Transloaders perform the dual task of loading and transporting while trucks are restricted to transporting only. These devices are generally diesel powered and, when operating underground, safety regulations require such vehicles to be equipped with a scrubber device to filter the exhaust of harmful gases and particles.

The transloader is typically a front-end loader with a bucket capacity ranging from six to eight cu yd. These vehicles can load themselves thus eliminating the need for a mucking machine. Cleaning out muck at corners is difficult with these large machines. The transloader is used to remove the muck from the tunnel face to the shaft or portal and dump it into a skip (hoist system) or disposal truck.

The diesel truck is a common piece of equipment in almost any construction activity. The trucks can be driven directly to the final disposal site, a distinct advantage. It is most economical for the trucks to be "double enders", with the ability to run backwards as fast as they run forwards. This eliminates turning around in the tunnel.

One of the main disadvantages of the rubber-tired diesel equipment is that they require about five times as much power to haul one ton of material as the conventional rail system. They also require about five times as much ventilation effort. But for many portal jobs, these disadvantages are far outweighed by the ability to run the trucks directly to the disposal area [3-26].

3.5.5 Hoist Systems

Hoist systems are employed to lift muck vertically out of a tunnel through a shaft. A two-skip system is a common piece of equipment which allows one skip (e.g. case, bucket, etc.) to be loaded at the bottom of the shaft while another is unloaded at ground surface.

The equipment consists of a big hoist mounted at ground surface with two drums. The head frame carries two skips with the loaded skip partially balanced by the descending empty skip.

3.6 CUT AND COVER CONSTRUCTION

For depths generally less than 60 ft, cut and cover is an alternative method for constructing shallow tunnels in soft ground soils. After considering pertinent design factors, such as local geology, soil characteristics, groundwater levels, and social and economic factors, the cut and cover construction method can often be more economical than tunneling methods [3-30]. Cut and cover construction may be employed:

a. when groundwater occurs or can be lowered to below the level of the tunnel construction; or

b. when existing soils from ground surface down to the level of the tunnel invert can be readily excavated.

3.6.1 Construction Methods

Procedures for cut and cover construction involve three basic steps: (1) excavation of all overburden soils from ground surface to the tunnel grade, (2) construction of the tunnel (typically by cast-in-place concreting), and (3) covering the tunnel with soil to the final design grade.

Often the most critical part of the cut and cover method involves the design and construction of the excavation. The design must assure stable excavation sidewalls (employing lateral support if necessary) and an adequate safety factor against upheaving or "blowing in" of the excavated bottom. Stable sidewalls can be provided by (1) open cut, (2) braced cut, (3) flexible bulkhead, and (4) slurry trench wall.

Open cut is a simple and cheap method of excavation. Most natural soils can be sloped to some angle β, where β equals the angle formed by the slope and a horizontal line. For dry cohesionless soils, slopes can have an unlimited height, provided the angle β is equal to or smaller than the angle of internal friction, ϕ, of the sand in a loose state. The slope stability of clays and other cohesive materials requires more detailed analysis. Taylor [3-31] has developed the concept of a stability number which can be used to establish the appropriate angle β. The stability number is a function of the cohesion and unit weight of the material and the slope's critical height.

Construction of open cuts therefore require additional land beyond the width of the excavation. The amount of additional area depends on the soil type and the depth of the excavation from ground surface. In many urban construction areas, this additional land is not available within the established tunnel right of way, preventing the use of the open cut method of excavation.

Lateral support methods such as sheeting, soldier pile and lagging, and slurry wall are all more expensive to construct, but permit completion of an excavation with vertical side walls. These methods typically involve the installation of two continuous parallel vertical walls spaced at a distance equal to the desired excavation width. Next, the soil between the vertical walls is excavated, and lateral supports consisting of tiebacks, struts, or other support means are installed at predetermined depths. Soil excavation continues until the bearing level of the subway system is reached.

The vertical side walls must be designed to withstand the expected earth and water pressures. Additional allowance must be made for surcharge loading, seepage effects, frost, temperature changes, etc. Design methods are adequately described in the literature [3-32, 3-33].

Once the excavation phase is completed, the tunnel construction can be started. After the tunnel structure is constructed, it is covered with compacted soil to final grade. In many instances, the excavated materials can be used as the cover material.

The excavation, construction, and backfilling operations must be scheduled to minimize disruption to normal street level activities.

3.6.2 Muck Characteristics

Cut and cover construction is generally performed in overburden soil deposits which can readily be excavated. A wide range of materials can therefore be expected, ranging from homogeneous clay, sand, and gravel deposits, to intermixed deposits such as glacial tills, to organic deposits, and finally to miscellaneous man-made fills comprising sand, gravel, boulders, clay and rubble materials.

During the excavation process, this material is transformed from its undisturbed in-situ state to a fully disturbed condition. This transformation has a drastic effect on the material's strength and compressibility characteristics, but very rarely changes its physical appearance. Particle to particle contact forces are broken apart and the material assumes a loose, uncompacted state when dumped onto the muck pile. Most soils can be recompacted to a density equal to or even greater than their natural in-situ state and thereby regain their original strenth properties. A more complete discussion of the strength and compressibility characteristics of both the disturbed excavated material and the recompacted material can be found in Section 4 of this report.

It should be noted that materials removed from a slurry trench will be mixed with bentonite clay slurry. The contaminated materials, however, will only be a small percentage of the total volume of material removed from the excavation. Use of the contaminated materials would have to be evaluated on an individual basis.

3.7 SPECIAL EXCAVATION TECHNIQUES

Variations in soil and ground water conditions have led to the development of techniques such as grouting and ground freezing and the recent development of the bentonite slurry tunneling shield. The following sections summarize some of the conditions for which these methods are applicable and the effect of these methods on muck properties.

3.7.1 Grouting

Some forms of grouting are an inherent part of tunneling processes. For example grouting is often required to fill the tailskin void created because the tunneling shield has a greater outside diameter than the primary lining. This grouting technique provides uniform support around the liner and has no direct effect on muck properties, except that surplus grout is often dumped into the muck cars.

Grouting activities completed to stabilize soil at the tunnel face will affect muck properties. Grouting may be required to decrease water inflow, reduce escape of compressed air, or strengthen the soil in order to improve stand-up times and minimize loss of ground and surface settlement. Penetration of grout into the soil depends on the gradation and permeability of the deposit. Thick viscous cement grouts suitable for "open" gravel deposits cannot be pumped into silty fine sands whereas chemical grouts such as AM-9 are suited to fine grained soil deposits. Frequently, combinations of grouts are used; for example, a cement grout used to fill large voids may be followed by a low viscosity chemical grout. The techniques for injecting grouts for tunneling projects have been described by numerous authors [3-34, 3-35, 3-36].

There are two general categories of grouts: (1) particulate grouts such as cement or clay and (2) chemical grouts. Grouts are injected into the ground as a fluid which after a measured set time forms a gel or solid inert substance. The set time is controlled by heat, pressure or catalysts mixed with the grout. In the case of multishot grouts, an injection of a second chemical is required to initiate the gel process. Some of the general properties of grouts are summarized in Table 3-5.

The muck obtained from grouted tunnels will vary in properties depending on the type of grout used. The Joosten silicate process, for instance, forms a hard soil and removal can require jackhammers or equilvalent ripping or excavating tools. Chunks of muck are friable to a weak sandstone. On the other hand, the one shot silicate grout produces soil with the consistency of a stiff clay which can be excavated by hand using pneumatic clay spades.

Chemical grouts such as resins and acrylamides will produce a wide range of properties as indicated by the strength data. Soil grouted with AM-9 has a gelatine-like appearance, very elastic and rubbery. Chucks of grouted soil can be easily broken apart by hand.

Grouting procedures will definitely affect the physical and chemical properties of muck. Each situation must be analyzed in order to fully evaluate the effect on a muck utilization process.

TABLE 3-5. SOIL CONDITIONS AND GROUT TYPES [3-36]

SOURCE: FLATAW

Soil Type	Minimum Particle Size, mm	Appropriate Grout Type	Typical Ground Strength, psi	Comments
Fissured Rock to Coarse Sand	5	Cement PFA Bentonite	High Low	Gel time controlled by additives
Coarse Sand to Medium Sand	1	2 "Shot" Silicate	300 to 1000	Joosten Process
		1 "Shot" Silicate	150 to 200	Catalyst required
Medium to Fine Sand	0.1	Resins (1)	10,000 to 20,000	Gel time variable from seconds to hours
Coarse Silt	0.01	Acrylamide (2)	280	Gel time variable from seconds to hours

(1) Includes phenol-formaldehyde, Tannin base resocorunal-formaldehyde, chrome lignins, and furfural.
(2) AM-9

3.7.2 Freezing

Controlled ground freezing has been used for over a century to aid in the construction of wells and mine shafts. The equipment, such as piping and refrigerants, can be selected to provide the most economical frozen ground barrier around the shaft or tunnel [3-37]. The frozen barrier prevents ground water seepage and provides an effective temporary support system [3-38, 3-39]. Following construction, the system is removed and the ground thaws to its previous condition.

An analysis of ground freezing phenomenon is complex, involving thermal properties and time effects of freezing in soils as well as the selection of the appropriate refrigeration equipment [3-40]. It has been pointed out, however, that despite the mathematical analysis, field data do not often fit the theoretical models. Therefore it is customary to instrument the frozen areas to monitor temperatures. One of the most reliable field tests involves probing the soil with a steel rod until the frozen surface is encountered.

During excavation, frozen ground is hard, but blasting is not normally required. Once the frozen soil has thawed, the physical properties show little effect of the freezing process.

3.7.3 Bentonite Tunneling Shield

The bentonite slurry tunneling shield has been developed to permit tunneling through water bearing soils without using compressed air, grouting or dewatering. The cutter-head of the specially designed shield rotates in a chamber filled with bentonite clay slurry. The pressurized chamber is sealed so that a stabilizing pressure can be applied to the mined face while normal atmospheric pressure is maintained inside the tunnel. The slurry also acts as the carrier fluid for pumping the muck to the surface [3-41]. At the surface, vibratory screens and hydrocyclones separate the muck from the slurry which is then returned to the tunnel. The muck is thus contaminated with remnants of the bentonite slurry, and its physical properties must be evaluated on an individual basis.

The tunnel shield performed satisfactorily in a trial section of the London Underground Fleet Line, accomplishing the mining without undue surface settlement [3-42, 3-43].

3.8 CONSTRUCTION EQUIPMENT OF THE FUTURE

The Advanced Research Projects Agency (ARPA), sponsored by the Defense Department and managed by the Bureau of Mines, has been investigating the application of modern and novel technology to the tunneling process. The research effort has covered the areas of geologic prediction, rock fragmentation and ground support systems. A summary of some of the novel techniques is shown in Table 3-6.

Since the techniques for rock fragmentation have only been evaluated in relatively small scale test situations, resulting muck properties can only be estimated.

TABLE 3-6. ROCK FRAGMENTATION AND SUPPORT SYSTEMS OF THE FUTURE [3-44]

Breakage Concept	Dimensionless Factor[1]
Thermal Methods	
High Power Laser (L)[2]	450
High Power Plasma (L)	120
Electron Beam Gun (L)	8
Hydraulic Methods	
Low Velocity Water Slugs (L)	85
High Pressure Continuous Jet Kerfing (L)	45
High Pressure Pulse Jets (L)	1
Solid, Nonexplosive Projectile Impact	
Medium Sized, Moderate Velocity Projectiles (L)	0.2
Large, High Velocity Projectiles (REAM GUN) (F)[3]	0.07
Combination Methods	
Mechanically-Assisted Hydraulic Jet Kerfing (F)	40
Mechanically-Assisted Thermal Fracture (F)	0.1
Mechanical Methods	
Sonic Energy Rock Kerfing (L)	1.5
Conical Borer (L)	0.7
High Energy Mechanical Impact (F)	1.5
Support Systems	
Thermal Methods - Rock Melting Subterranes	

[1] $\frac{\text{Specific energy}}{\text{Compressive strength of rock removed}}$

SOURCE: OLSON; p. 1510

[2] (L) = Laboratory experiment

[3] (F) = Field test

3.8.1 Thermal Methods

Thermal methods involve the application of heat to the rock, either at the surface or within the rock mass. Various modes of thermal rock fracture have been defined including spalling, surface heat weakening, rock melting and vaporization [3-45].

High powered electron beams or lasers have been used to melt kerfs in rock masses. Rock blocks are formed by kerfing around design perimeter of the block. The problem of removing these 4 x 4 x 2 ft blocks from the parent-rock mass has not been evaluated, but preliminary estimates indicate that the method could produce an advance rate of 190 ft per day for an 8 x 8 ft tunnel.

It thus appears that rock blocks could be produced which might be utilized in architectural sidewalks or riprap for channels. However, geologic factors such as jointing and rock durability must first be evaluated.

3.8.2 Projectile Impact

The use of standard military guns to shoot concrete projectiles into rock is, perhaps, the method which could be most quickly adapted for tunnel construction. The high energy projectiles can dislodge from 1 to 1.25 tons of rock at each impact. A crater is formed, yet in full scale field tests, overbreak was not severe. Noise, dust and safety controls have to be developed, but the basic hardware is readily available. The values of specific energy (energy required to remove a unit volume of rock) are even lower than standard drill and blast methods [3-46]. A comparison of specific energy requirements for various excavation methods is included in Table 3-7.

Since the method parallels the drill and blast concept, it is anticipated that the muck would also be similar to drill and blast muck. In one test of the method, the muck ranged from fine powder to pieces as large as 1000 lb. Most pieces were in the range of two to thirty lb and were handled by an EIMCO 911 LHD Mucker.

TABLE 3-7. COMPARISON OF SPECIFIC ENERGY FOR ROCK FRAGMENTATION [3-46]

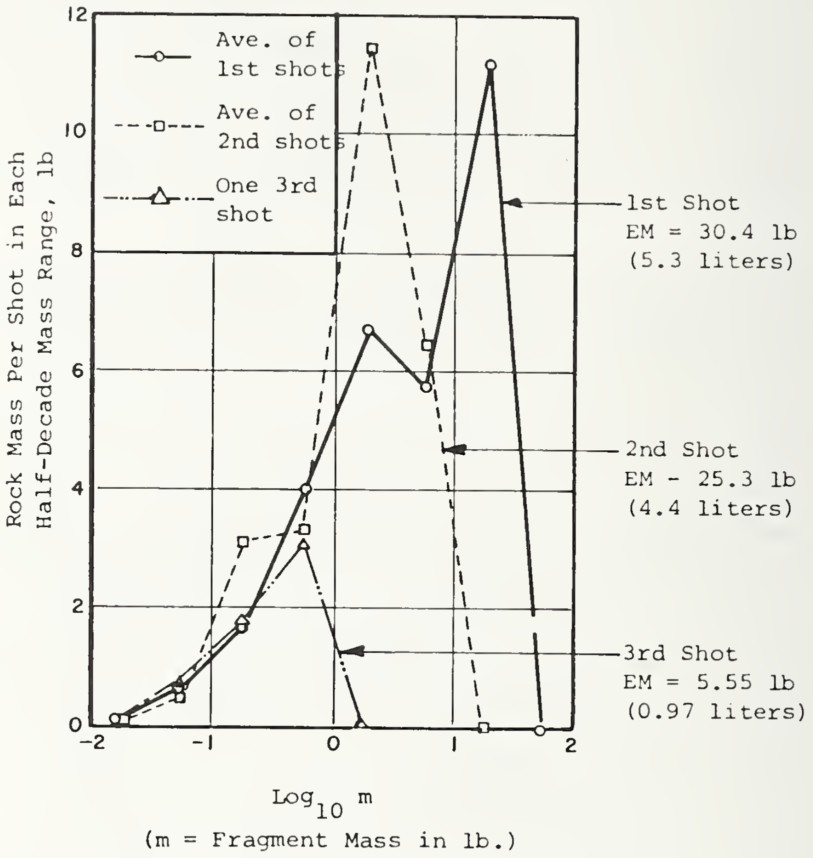
SOURCE: LUNDQUIST; p. 827

Method	Specific Energy(1) (in.-lb/in.^{3})
REAM	1,490
Drill and Blast	5,300
Tunneling Machine	15,000
Percussive Drilling (small diameter)	36,000
Water Jets	600,000
Subterrane	750,000
Thermal Spalling	2,400,000

(1) For excavation in granite.

3.8.3 Water Cannon

High pressure water cannons can produce pressures ranging from 125,000 to 650,000 psi which are sufficient to disintegrate rock. Jet velocities approaching 10,000 fps are obtained. Both continuous jets and pulsed jets have been developed; the latter is capable of supplying the extremely high pressures [3-47, 3-48]. The jet craters the rock and produces thin fractures. Subsequent shots directed at the fractures can then produce larger openings. In tests with a dolomitic limestone, with jet pressures of 450,000 psi, 14 shots removed an average volume of 0.035 cu ft per shot. Figure 3-20 illustrates the gradation of muck produced from the test series. It appears that the method will result in muck similar to drill and blast muck with the exception that very few, if any, fine particles (sand size and smaller) are produced.



Note: Dolomitic limestone muck for standoff = 2 to 4 in., Pulse energy = 97,000 ft-lb with vacuum in Nozzle

FIGURE 3-20. SIZE DISTRIBUTION OF MUCK PRODUCED BY A WATER CANNON [3-48]

SOURCE: COOLEY; p. 819

3.8.4 Rock Melting

Rock or soil melting techniques can produce a glass-like zone around the perimeter of a tunnel, scaling out ground water and providing a primary support system [3-49, 3-50]. When used in this manner, the materials excavated from within the tunnel are unaffected by the melting process. The muck, therefore, will be similar to soft ground muck or muck produced by standard mining techniques.

4. PROGRAM OF SUBSURFACE INVESTIGATION

4.1 INTRODUCTION

Prudent design of underground structures requires the completion of a subsurface exploration program. The purpose of the program is to accurately evaluate the subsurface conditions in order to predict the behavior of the ground and structure during and after construction. The scope of a subsurface exploration program is a function of the anticipated subsurface conditions, the importance of the structure under construction, and the importance of adjacent structures. The latter two factors usually dictate a very comprehensive exploration program for urban transportation systems. Accurate data are necessary both for the design and construction of the subway itself and for the underpinning of adjacent structures.

This section contains a brief description of subsurface exploration procedures currently in use for urban transportation systems, an evaluation of the additional investigations which are necessary to plan for muck utilization, and cost estimates for the additional investigations. Brief descriptions of current subsurface procedures are presented in order to indicate the value of typical design data in the analysis of muck properties.

4.2 TRADITIONAL METHODS OF SUBSURFACE EXPLORATION AND TESTING

4.2.1 Field Exploration

Nearly all subsurface exploration programs for large projects begin with a survey of existing soil and rock conditions. Typically, the survey includes a geological reconnaissance of the entire site, a literature review, and an evaluation of previous construction experience. The geological reconnaissance includes field mapping, with particular emphasis on a description of soil and rock types and the presence of adverse geological features such as faults. Aerial photographs frequently supplement geological studies. General information about the character of the subsurface conditions at the site in question and the performance of existing structures in similar soil and rock deposits can usually be found in literature.

Actual subsurface explorations for tunneling projects usually begin with widely spaced preliminary test borings. These test borings provide information about subsurface soil, rock, and groundwater conditions along the proposed route alignments and contribute to the selection of a final alignment. The preliminary test boring data may dictate changes in the proposed tunnel alignment. Horizontal changes are generally not made unless the subsurface conditions are very unfavorable. Not only would horizontal alignment changes necessitate additional explorations, but they may result in a less effective transportation corridor. Changes in vertical alignment are somewhat easier to make depending on the subsurface stratigraphy and are sometimes used to place the tunnel in more favorable tunneling ground.

Having established the final alignment, the so-called design phase explorations are made to assist in structual design and construction. Design phase explorations are more closely spaced and comprehensive, and sampling and testing at the location of the proposed tunnels are more detailed. As a minimum, these explorations provide sufficient data to accurately describe the stratigraphy and to evaluate groundwater conditions. In addition, investigators should be sensitive to the identification and location of adverse geologic features such as sand deposits in clay, boulders, weathering, and faults which can cause problems during design or construction and which can greatly increase the cost of the project.

Test borings are the most common method of subsurface exploration in use today. Test borings are a relatively inexpensive way to obtain actual samples of the materials encountered. Moreover, many standard field testing procedures for both soil and rock have been developed for use with test borings. Other methods of direct-observation explorations which are available include test pits in soil and pilot tunnels in rock. These latter methods are expensive, especially in urban environments, and are usually resorted to only in extraordinary circumstances.

The most common type of field test used in test borings is the Standard Penetration Test (SPT). A SPT is performed by driving a standard split spoon sampler (typically 2.0 in. outside diameter) into the ground with a 140 lb weight falling freely for 30 in. The penetration resistance (N) represents the number of blows necessary to drive the sample one ft. Values of the penetration resistance have been empirically correlated to the density or consistency of soil as shown below. The cone penetration test (CPT) is another field method used to measure soil density. However, this test is not used widely in the United States.

Fine-grained Soils		Coarse-grained Soils	
N	Consistency	N	Density
0 - 2	Very soft	0 - 4	Very loose
2 - 4	Soft	4 - 10	Loose
4 - 8	Medium	10 - 30	Medium
8 - 15	Stiff	30 - 50	Compact
15 - 30	Very stiff	50+	Very compact

Refusal encountered during SPT, typically defined as no penetration for 100 blows, is sometimes assumed to represent the location of competent bedrock. This procedure is not dependable, however, because refusal can be encountered for many other reasons such as boulders, obstructions, or weathered bedrock. Rock coring should be used to check the level of the bedrock if this is an important variable. Seismic surveys are another means to verify the location of bedrock, but they are generally not possible in urban areas because of the confined working area and high background noise and vibration levels.

In fine-grained soils, it is possible to measure soil strength and consistency by the field vane shear test. This test is performed by pushing a steel vane of known dimensions into the soil at the bottom of a boring and turning it carefully with a known force. The force at failure and subsequent to failure are measured in order to determine the ultimate and residual soil strengths. As described later in this section, comparison of the ultimate and residual strengths is a measure of soil sensitivity.

Water table observations and permeability tests are commonly made within completed test borings. Frequently an observation well is installed, and water table observations are obtained for an extended period of time to determine the static water level at the test boring location. Permeability tests in soil are commonly made by pumping water out of the boring and measuring water table drawdown at various locations. In rock, permeability tests are usually conducted by pumping water into a specific length of the test boring, at a given pressure, and measuring the time rate of water flow.

Other test boring procedures which are common in rock are oriented core borings and borehole photography. Both of these procedures are used to identify the orientation of rock mass discontinuities such as joints, foliation and bedding planes. Knowledge of the specific orientation and location of a discontinuity is necessary if its effect on the performance of the excavation opening is to be properly evaluated. Many of the geophysical borehole techniques which are common in oil well drilling are not used very often for this type of investigation. One common type of geophysical procedure which cannot usually be used in an urban area because of stray electric currents is the electrical resistivity survey.

4.2.2 Laboratory Testing

Upon completion of the test borings, representative specimens of the soil and rock samples are used for laboratory testing. Initially, tests are performed to properly identify and classify the materials recovered from the test borings. Proper classification of subsurface materials is absolutely essential. Secondly, significant engineering properties of the materials relative to their strength, compressibility and permeability are measured for use in design and construction computations.

Generally, the color, odor, unit weight, and texture of the samples are recorded. Odor is particularly important as an indication of organic content and possibly groundwater contamination where the water may contain detrimental dissolved minerals. The unit weight of clayey soils and rock is relatively easy to measure because samples of these soils remain intact unless severely handled. However, undisturbed techniques for sampling sandy soils do not permit accurate determination of unit weight.

Texture refers to the size and shape of individual soil particles and the mode of interparticle contact. Particle size varies from clays and silts, which cannot be seen as individual particles, to sand, gravel and boulders. Particle shape can be flat, rounded or angular. The distribution of particle sizes as determined by a sieve analysis is an important characteristic of granular soils.

4.2.2.1 Clay Soils

In addition to the above criteria, the natural water content, Atterberg limits, strength, and compressibility properties of fine-grained soils are commonly determined for design and contruction purposes. The natural water content, expressed as a percent, is easily determined by weighing a soil sample before and after it is dried in a controlled-temperature oven. This is an important index property of fine-grained soils, especially when used in conjunction with other test results as described later in this section.

The Atterberg limits are a measure of the water contents at which fine-grained soils change states from semisolid to plastic (plastic limit) and from plastic to liquid (liquid limit). Standard laboratory procedures have been developed to measure these water contents [4-1]. The plasticity index is defined as the difference in water content between the liquid and plastic limits. In general the larger this value, the more clayey is the soil.

Atterberg limits are used in conjunction with the Plasticity Chart shown in Figure 4-1 to classify fine-grained soils. As shown in the chart, a soil can be classified as either silt or clay depending on the values of the liquid limit and plasticity index. This classification method for silts and clays is part of the commonly used Unified Soil Classification System given in Table 4-1.

The short-term or undrained strength of clayey soils is most often measured in the laboratory by a simple test called the unconfined compression test [4-1]. A cylinder of undisturbed clay, about 1.4 in. in diameter and 3.0 in. high, is compressed axially until it fails. The failure stress, quoted in pounds per square inch (psi) or tons per square foot (tsf) is then used to identify soil consistency as shown below:

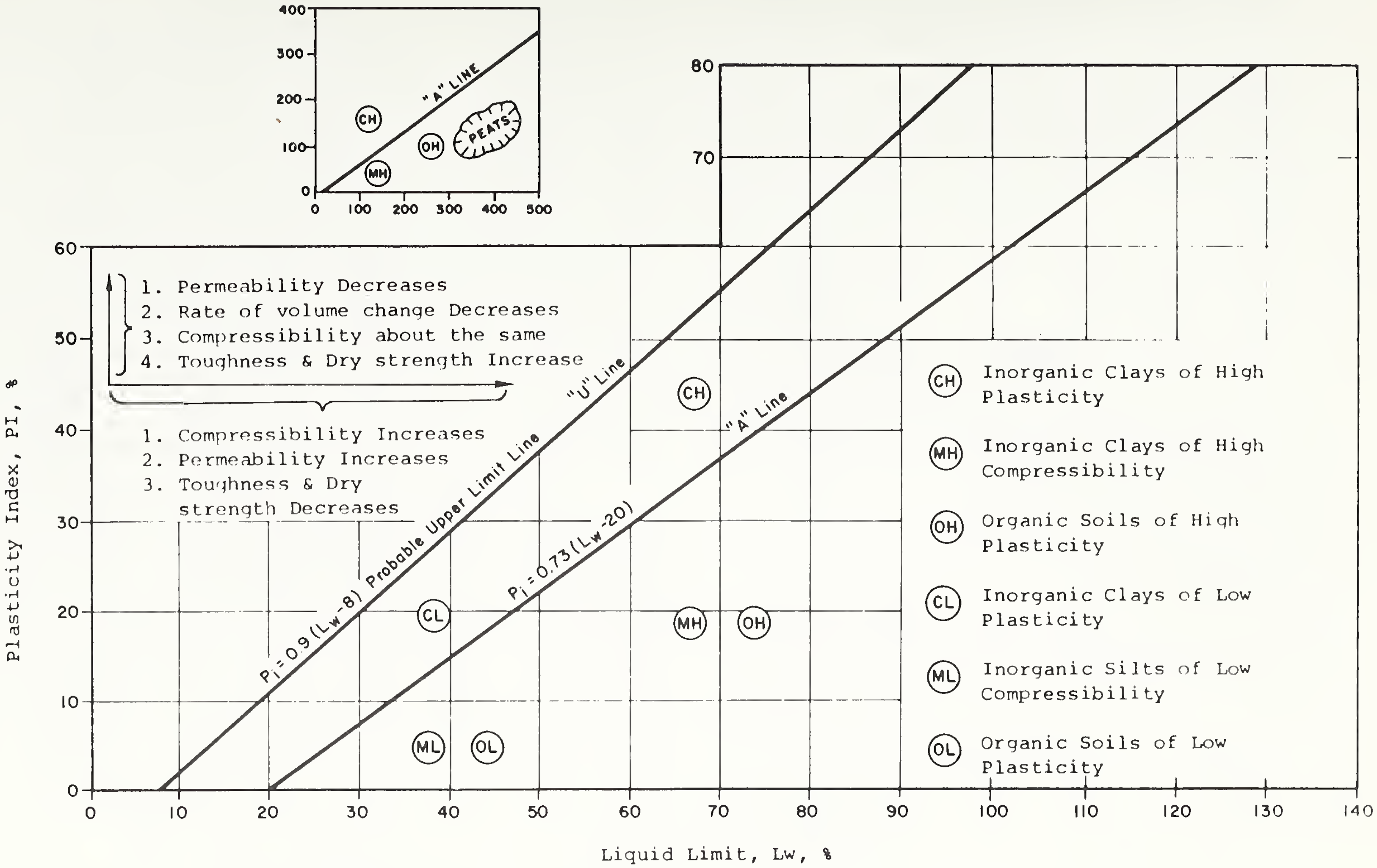
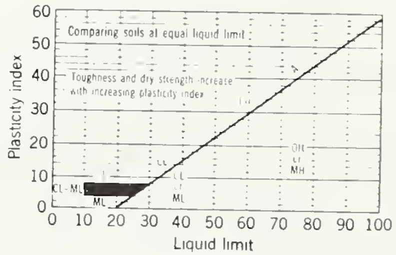


FIGURE 4-1. PLASTICITY CHART FOR IDENTIFICATION OF CLAYS AND SILTS

TABLE 4-1. UNIFIED SOIL CLASSIFICATION CHART

Field Identification Procedures (Excluding particles larger than 3 in. and basing fractions on estimated weights)				Group Symbols[a]	Typical Names	Information Required for Describing Soils		Laboratory Classification Criteria	
Coarse-grained soils More than half of material is *larger* than No. 200 sieve size[b] (The No. 200 sieve size is about the smallest particle visible to naked eye)	Gravels More than half of coarse fraction is larger than No. 7 sieve size (For visual classification, the ¼ in. size may be used as equivalent to the No. 7 sieve size)	Clean gravels (little or no fines)	Wide range in grain size and substantial amounts of all intermediate particle sizes	*GW*	Well graded gravels, gravel-sand mixtures, little or no fines	Give typical name; indicate approximate percentages of sand and gravel; maximum size; angularity, surface condition, and hardness of the coarse grains; local or geologic name and other pertinent descriptive information; and symbols in parentheses For undisturbed soils add information on stratification, degree of compactness, cementation, moisture conditions and drainage characteristics Example: *Silty sand*, gravelly; about 20% hard, angular gravel particles ½-in. maximum size; rounded and subangular sand grains coarse to fine, about 15% non-plastic fines with low dry strength; well compacted and moist in place; alluvial sand; (*SM*)	Use grain size curve in identifying the fractions as given under field identification Determine percentages of gravel and sand from grain size curve Depending on percentage of fines (fraction smaller than No. 200 sieve size) coarse grained soils are classified as follows: Less than 5% *GW, GP, SW, SP* More than 12% *GM, GC, SM, SC* 5% to 12% *Borderline* cases requiring use of dual symbols	$C_U = \frac{D_{60}}{D_{10}}$ Greater than 4 $C_C = \frac{(D_{30})^2}{D_{10} \times D_{60}}$ Between 1 and 3	
			Predominantly one size or a range of sizes with some intermediate sizes missing	*GP*	Poorly graded gravels, gravel-sand mixtures, little or no fines			Not meeting all gradation requirements for *GW*	
		Gravels with fines (appreciable amount of fines)	Nonplastic fines (for identification procedures see *ML* below)	*GM*	Silty gravels, poorly graded gravel-sand-silt mixtures			Atterberg limits below "A" line, or *PI* less than 4	Above "A" line with *PI* between 4 and 7 are *borderline* cases requiring use of dual symbols
			Plastic fines (for identification procedures, see *CL* below)	*GC*	Clayey gravels, poorly graded gravel-sand-clay mixtures			Atterberg limits above "A" line, with *PI* greater than 7	
	Sands More than half of coarse fraction is smaller than No. 7 sieve size	Clean sands (little or no fines)	Wide range in grain sizes and substantial amounts of all intermediate particle sizes	*SW*	Well graded sands, gravelly sands, little or no fines			$C_U = \frac{D_{60}}{D_{10}}$ Greater than 6 $C_C = \frac{(D_{30})^2}{D_{10} \times D_{60}}$ Between 1 and 3	
			Predominantly one size or a range of sizes with some intermediate sizes missing	*SP*	Poorly graded sands, gravelly sands, little or no fines			Not meeting all gradation requirements for *SW*	
		Sands with fines (appreciable amount of fines)	Nonplastic fines (for identification procedures, see *ML* below)	*SM*	Silty sands, poorly graded sand-silt mixtures			Atterberg limits below "A" line or *PI* less than 5	Above "A" line with *PI* between 4 and 7 are *borderline* cases requiring use of dual symbols
			Plastic fines (for identification procedures, see *CL* below)	*SC*	Clayey sands, poorly graded sand-clay mixtures			Atterberg limits below "A" line with *PI* greater than 7	

		Identification Procedures on Fraction Smaller than No. 40 Sieve Size					
		Dry Strength (crushing characteristics)	Dilatancy (reaction to shaking)	Toughness (consistency near plastic limit)	Group Symbols[a]	Typical Names	Information Required for Describing Soils
Fine-grained soils More than half of material is *smaller* than No. 200 sieve size (The No. 200 sieve size is about the smallest particle visible to naked eye)	Silts and clays liquid limit less than 50	None to slight	Quick to slow	None	*ML*	Inorganic silts and very fine sands, rock flour, silty or clayey fine sands with slight plasticity	Give typical name; indicate degree and character of plasticity, amount and maximum size of coarse grains; colour in wet condition, odour if any, local or geologic name, and other pertinent descriptive information, and symbol in parentheses For undisturbed soils add information on structure, stratification, consistency in undisturbed and remoulded states, moisture and drainage conditions Example: *Clayey silt*, brown; slightly plastic; small percentage of fine sand; numerous vertical root holes; firm and dry in place; loess; (*ML*)
		Medium to high	None to very slow	Medium	*CL*	Inorganic clays of low to medium plasticity, gravelly clays, sandy clays, silty clays, lean clays	
		Slight to medium	Slow	Slight	*OL*	Organic silts and organic silt-clays of low plasticity	
	Silts and clays liquid limit greater than 50	Slight to medium	Slow to none	Slight to medium	*MH*	Inorganic silts, micaceous or diatomaceous fine sandy or silty soils, elastic silts	
		High to very high	None	High	*CH*	Inorganic clays of high plasticity, fat clays	
		Medium to high	None to very slow	Slight to medium	*OH*	Organic clays of medium to high plasticity	
Highly Organic Soils		Readily identified by colour, odour, spongy feel and frequently by fibrous texture			*Pt*	Peat and other highly organic soils	



Plasticity chart
for laboratory classification of fine grained soils

From Wagner, 1957.

[a] *Boundary classifications.* Soils possessing characteristics of two groups are designated by combinations of group symbols. For example *GW-GC*, well graded gravel-sand mixture with clay binder.

[b] All sieve sizes on this chart are U.S. standard.

Field Identification Procedure for Fine Grained Soils or Fractions

These procedures are to be performed on the minus No. 40 sieve size particles, approximately 1/64 in. For field classification purposes, screening is not intended, simply remove by hand the coarse particles that interfere with the tests.

Dilatancy (Reaction to shaking):

After removing particles larger than No. 40 sieve size, prepare a pat of moist soil with a volume of about one-half cubic inch. Add enough water if necessary to make the soil soft but not sticky.

Place the pat in the open palm of one hand and shake horizontally, striking vigorously against the other hand several times. A positive reaction consists of the appearance of water on the surface of the pat which changes to a livery consistency and becomes glossy. When the sample is squeezed between the fingers, the water and gloss disappear from the surface, the pat stiffens and finally it cracks or crumbles. The rapidity of appearance of water during shaking and of its disappearance during squeezing assist in identifying the character of the fines in a soil.

Very fine clean sands give the quickest and most distinct reaction whereas a plastic clay has no reaction. Inorganic silts, such as a typical rock flour, show a moderately quick reaction.

Dry Strength (Crushing characteristics):

After removing particles larger than No. 40 sieve size, mould a pat of soil to the consistency of putty, adding water if necessary. Allow the pat to dry completely by oven, sun or air drying, and then test its strength by breaking and crumbling between the fingers. This strength is a measure of the character and quantity of the colloidal fraction contained in the soil. The dry strength increases with increasing plasticity.

High dry strength is characteristic for clays of the CH group. A typical inorganic silt possesses only very slight dry strength. Silty fine sands and silts have about the same slight dry strength, but can be distinguished by the feel when powdering the dried specimen. Fine sand feels gritty whereas a typical silt has the smooth feel of flour.

Toughness (Consistency near plastic limit):

After removing particles larger than the No. 40 sieve size, a specimen of soil about one-half inch cube in size, is moulded to the consistency of putty. If too dry, water must be added and if sticky, the specimen should be spread out in a thin layer and allowed to lose some moisture by evaporation. Then the specimen is rolled out by hand on a smooth surface or between the palms into a thread about one-eight inch in diameter. The thread is then folded and re-rolled repeatedly. During this manipulation the moisture content is gradually reduced and the specimen stiffens, finally loses its plasticity, and crumbles when the plastic limit is reached.

After the thread crumbles, the pieces should be lumped together and a slight kneading action continued until the lump crumbles.

The tougher the thread near the plastic limit and the stiffer the lump when it finally crumbles, the more potent is the colloidal clay fraction in the soil. Weakness of the thread at the plastic limit and quick loss of coherence of the lump below the plastic limit indicate either inorganic clay of low plasticity, or materials such as kaolin-type clays and organic clays which occur below the A-line.

Highly organic clays have a very weak and spongy feel at the plastic limit.

Consistency	Unconfined Compressive Strength (tsf)
Very Soft	Less than 0.25
Soft	0.25 - 0.50
Medium	0.50 - 1.0
Stiff	1.00 - 2.00
Very Stiff	2.00 - 4.00
Hard	Greater than 4.00

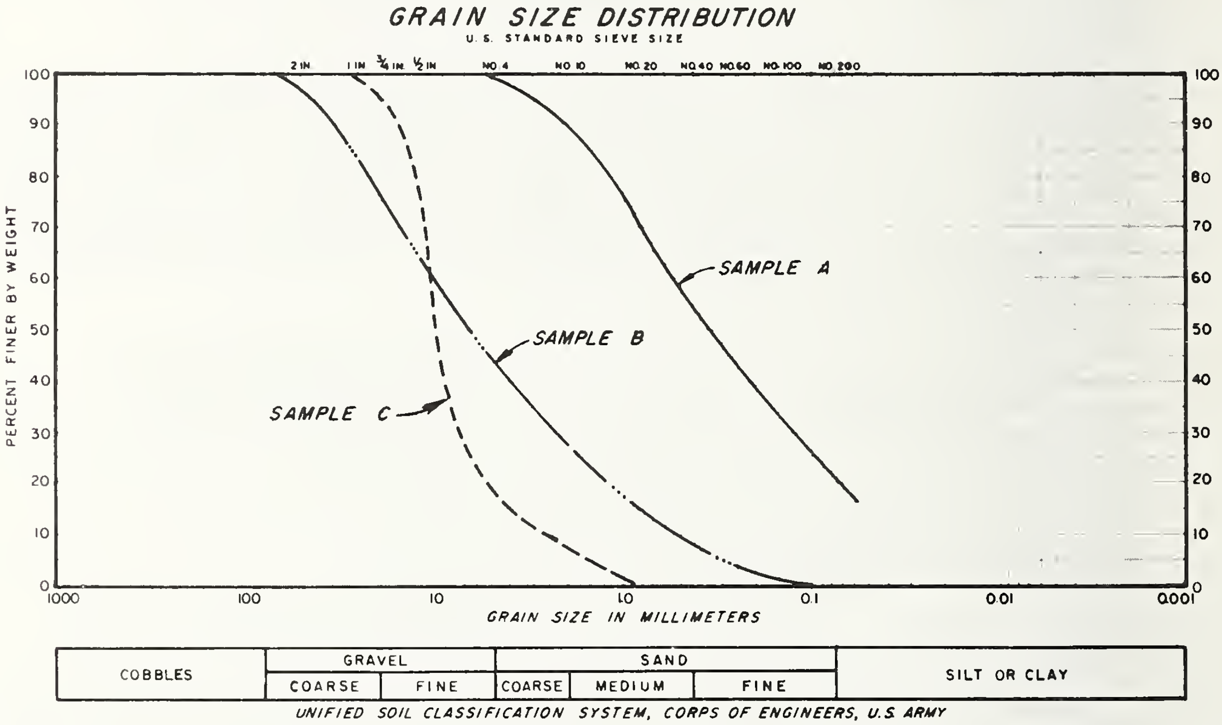
Soil sensitivity is defined as the ratio of undisturbed to remolded, undrained strength. There is no standard procedure for determining sensitivity in the laboratory because the method of remolding can affect the remolded strength determination. The best way to determine remolded strength is in the field by the vane test, described previously. Nevertheless, assuming that the undisturbed and remolded strengths are known, the following system can be used to determine soil sensitivity:

Sensitivity	Ratio of Undisturbed to Remolded Strength
Normal	Less than 4
Sensitive	4 - 8
Extrasensitive	8 - 16
Quick	Greater than 16

Compressibility characteristics of fine-grained soils are determined by the one-dimensional consolidation test [4-1]. In this test, a sample of soil, usually 2.5 in. in diameter and 0.75 in. thick, is carefully fitted into a steel ring and compressed under controlled conditions. The steel ring prevents lateral expansion of the soil. Measurements of sample deflection during compression are made to permit calculation of the time-rate of compression. The compression is due both to water being squeezed out of the soil structure and to creep of the soil structure itself.

4.2.2.2 Sand and Gravel Soils

A mechanical sieve analysis is the most common classification test for coarse-grained or mixed-grained soils. To perform this test, a dry soil sample is placed in a set of sieves with decreasing opening sizes and shaken vigorously. The grain size distribution is determined by weighing the amount of soil retained on each sieve. Several typical grain size curves with appropriate descriptions are shown in Figure 4-2. Grain size distribution can be related to many important engineering properties such as compaction characteristics, permeability and frost susceptibility. Several index properties such as the effective particle size and the coefficients of uniformity and curvature are derived from the grain size curve as described in Section 3.



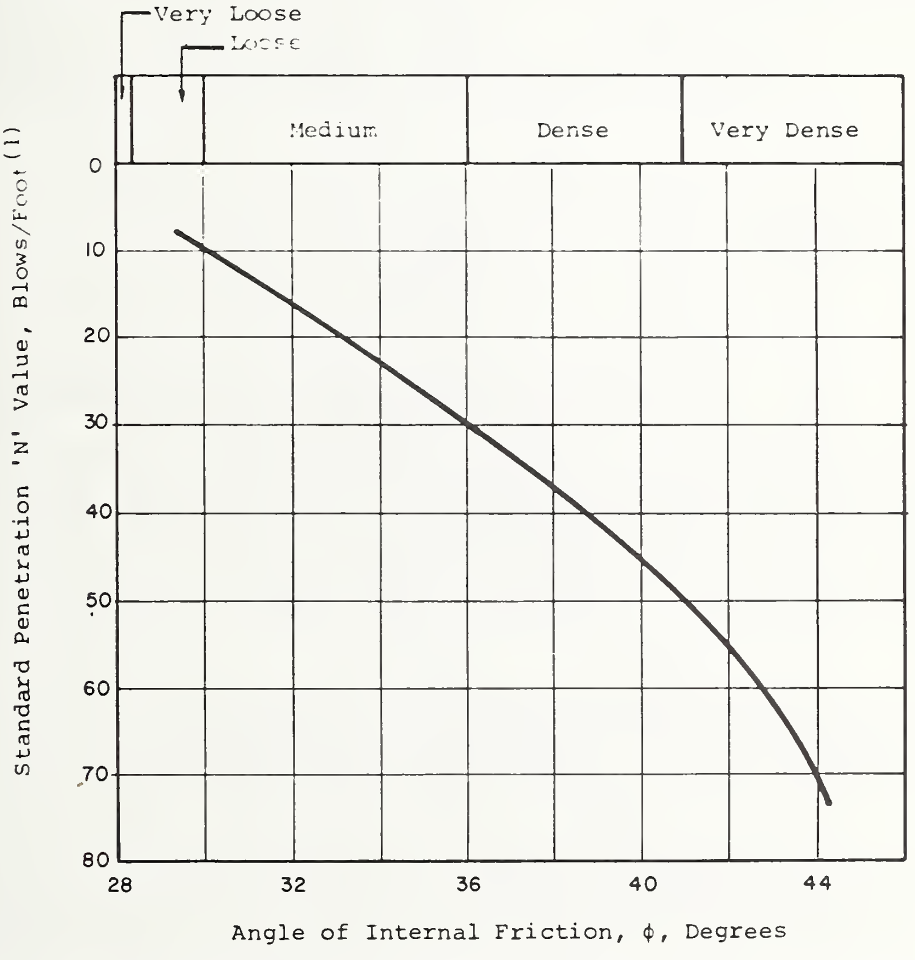
Sample No.	Description
A	Well graded coarse to fine SAND, some silt
B	Well graded sandy coarse to fine GRAVEL
C	Uniformly graded fine GRAVEL, some sand

FIGURE 4-2. TYPICAL GRADATION CURVES - SAND AND GRAVEL

The strength of a sand deposit is a function of the frictional resistance and the degree of interlocking between individual particles. Strengths for different degrees of density are determined in the laboratory by either triaxial or direct shear tests. In general, the confining pressure on a test sample is varied and the amount of force needed for failure is measured. The relationship is characterized by the angle of internal friction. Typical values are given below:

Angle of Internal Friction in Degrees [4-2]

Material	Material Density	
	Loose	Dense
Uniform Round Sand	27.5	34
Well-Graded Angular Sand	33	45
Sandy Gravel	35	50
Silty Sand	27 - 33	30 - 34
Silt	27 - 30	30 - 35



Note:

(1) 'N' value defined as the number of blows required to drive a two inch O.D. standard split spoon sampler one foot with a 140 lb hammer free falling 30 inches.

FIGURE 4-3. STANDARD PENETRATION RESISTANCE ('N' VALUE) VERSUS ANGLE OF INTERNAL FRICTION FOR SANDS [4-3]

SOURCE: PECK; p. 310

Empirical relationships have also been developed that relate the angle of internal friction to the "N" value determined by the standard penetration test. This relationship is illustrated in Figure 4-3.

4.2.2.3 Rock

Laboratory testing of intact rock is used primarily for identification and classification because rock mass properties are largely controlled by geologic discontinuities in the rock mass, rather than intact rock properties. Intact properties do, however, provide an upper limit of rock mass strength and a lower limit of rock mass compressibility.

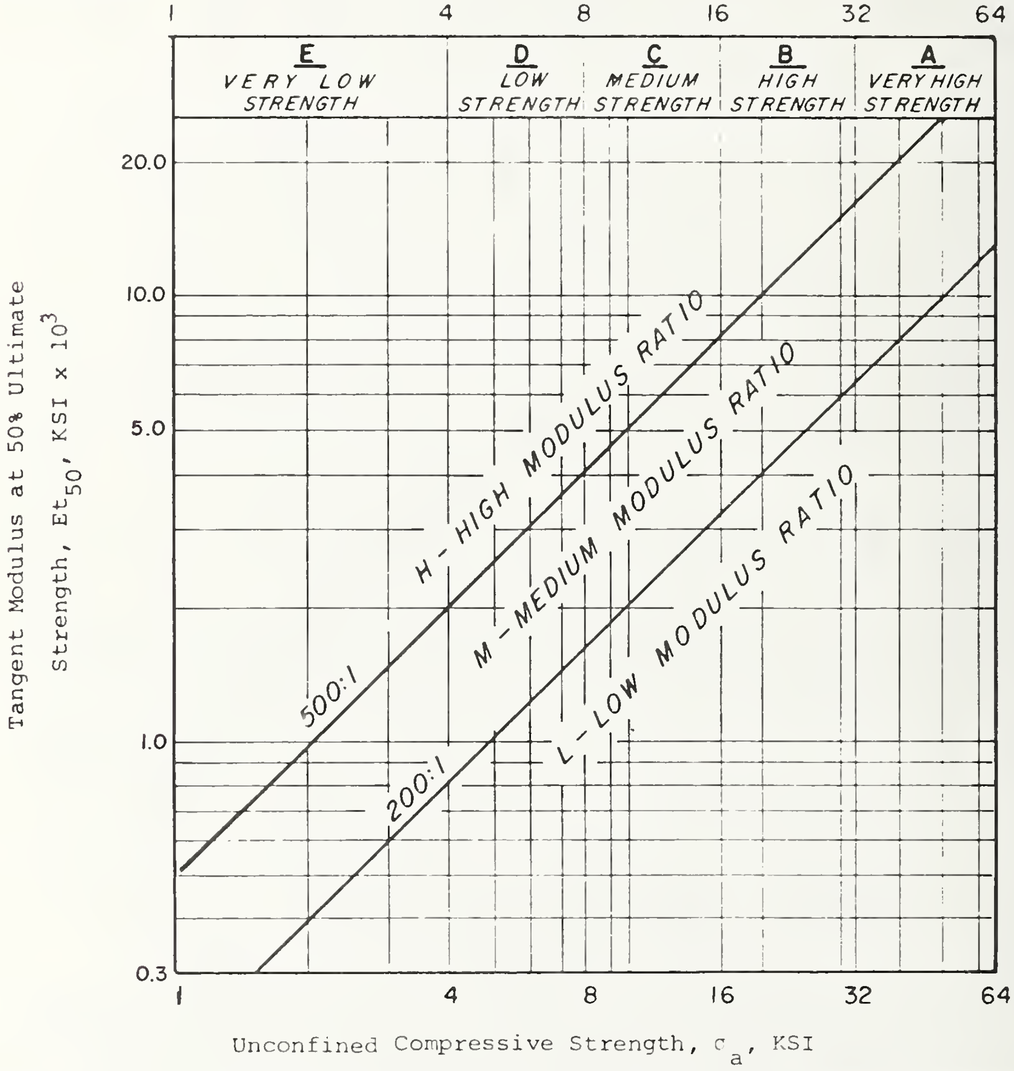


FIGURE 4-4. TANGENT MODULUS VERSUS UNCONFINED COMPRESSIVE STRENGTH OF INTACT ROCK [4-4]

SOURCE: DEERE; p. 136

An unconfined compression test on a cylindrical sample of intact rock is a standard method used to assess rock strength in the laboratory. The test procedure is an extension of the tests conducted on soil samples except that failure stresses in rock are much greater than soil failure stresses. The results of unconfined compression tests provide an indication of both rock strength and compressibility. A widely used engineering classification system shown in Figure 4-4 is based on the results of unconfined compression testing together with a geological description [4-4]. During unconfined testing, the sonic velocity of the rock can also be measured for a comparison with the rock mass siesmic velocity. This comparison gives one estimate of the amount of fracturing in the rock mass.

Strength and compressibility for rock masses are evaluated by field testing. Field tests may involve plate bearing tests, overcoring techniques, sonic tests, or seismic tests. Since rock jointing can influence the test results, the data must be interpreted by a qualified engineering geologist. The effects of geometry and rock jointing can affect plate load tests in tunnels [4-5].

With the increase in use of machine mining, rock hardness testing is becoming more common. Both rebound hardness and abrasion hardness are determined for a measure of the so-called "total" hardness [4-6]. In some cases, special tests are performed on shale samples to determine slake durability and creep or swell potential [4-7].

4.2.3 Evaluating the Potential for Muck Utilization

Tunnel muck is composed of the soil and rock materials removed during excavation of the tunnel. Samples of these materials can be obtained and tested during the subsurface exploration program. The question arises whether or not it is possible to evaluate the potential for muck utilization based on the field and laboratory data obtained for design and construction purposes. To a large degree this is in fact possible, provided the data are viewed from a slightly different perspective.

Presented in this section is a description of muck and a discussion of how the currently available field and laboratory data can be used to define its engineering properties. Section 4.3 and 4.4 contain discussions of recommended additional field and laboratory test procedures and cost estimates.

Soil and rock data obtained for design and construction purposes are very helpful for evaluating the character of tunnel muck. Many of the soil tests are completed on disturbed samples and provide direct input to the evaluation.

The effect of water accumulation can be significant for fine-grained muck because the muck will have low permeability, and the water cannot be easily removed. In coarse-grained muck the water will easily drain away. The amount of water accumulation is a function of the amount of groundwater infiltration into completed portions of the tunnel, weather conditions, and construction procedures; none of which can be evaluated prior to construction. For the present, it is important to realize that water can have a softening effect on fine-grained muck and that this problem cannot be quantitively evaluated by the test procedures currently utilized for design and construction purposes. This problem and its relation to the recommended additional testing procedures are discussed in Section 4.3.

It is not possible to evaluate the effect of construction debris on muck properties using current testing procedures. Debris is present in all tunnel muck. Although debris almost always constitutes a small percentage of the total volume or weight of muck, it can cause problems relative to muck utilization.

The remainder of this section discusses muck characteristics based on mining operations and a discussion of how standard field and laboratory test data can be used to evaluate engineering properties of muck. The discussion is divided into four major categories: clay-based muck, sand and gravel-based muck, rock-based muck, and tunneling debris.

4.2.3.1 Clay-based Muck

Tunneling in clay falls into the general category of soft ground tunneling. A "Tunnelman's Classification" system originally developed by Terzaghi and recently expanded by Fenix & Session is presented in Table 4-2. The system relates a general miner's description of soil conditions to standard soil engineering classification terminology.

Hard and stiff clay deposits can be mined either by machine or by hand. A cutter wheel shield produces small clay chips; excavator shields produce large chunks which are broken apart during the mucking, loading and unloading process. Hand mining with clay spades in hard clay produces chunks typically measuring 6 x 6 x 3 in. In stiff clay, hand mining is accomplished with clay spades or clay knives. The clay knife is formed from a steel hoop about 12 in. in diameter. The miner forces one side of the hoop against the clay while a tugger hoist pulls the hoop across the face. A long semi-circular chunk of clay is thus carved out of the face.

Soft clay is quite often mined with the aid of compressed air or by bulkheading the forward diaphragm of the tunnel shield and squeezing the clay into the tunnel (intrusion method). Soft clay is extremely difficult to mine by hand tools; sometimes clay knives are used, but in either case the material is very heavy, sticky and hard to handle.

In the intrusion method the clay can be taken in through either the upper or lower portions of the bulkheads. The clay is squeezed through ports located in the bulkhead and enters as large strips having a somewhat toothpaste-like consistency. Wire cutters are often used to slice the ribbon-like strips into lengths suitable for loading into the muck cars.

TABLE 4-2. TUNNELMAN'S GROUND CLASSIFICATION [4-8] (Based on Terzaghi's principal categories of ground with 3(*) additions)

SOURCE: FENNIX & SCISSOR; p. 11

No.	Ground Classification	Tunnel Working Conditions	Representative Soil Types
1	*Hard	Tunnel heading may be advanced without roof support.	Very hard calcareous clay; cemented sand and gravel.
2	Firm	Tunnel heading can be advanced without roof support, and the permanent support can be constructed before the ground will start to move.	Loess above the water table; various calcareous clays with low plasticity such as the marls of South Carolina.
3	Slow Raveling	Chunks or flakes of material begin to drop out of the roof or the sides sometime after the ground has been exposed.	Fast Raveling occurs in residual soils or in sand with clay binder below the water table. Above the water table the same soils may be Slow Raveling or even Firm.
4	Fast Raveling	In Fast Raveling ground the process starts within a few minutes; otherwise it is referred to as Slow Raveling.	
5	Squeezing	Ground slowly advances into tunnel without fracturing and without perceptible increase of water content in ground surrounding the tunnel. (May not be noticed in tunnel but cause surface subsidence.)	Soft or medium-soft clay.
6	Swelling	Like squeezing Ground, moves slowly into tunnel, but the movement is associated with a very considerable volume increase in the ground surrounding the tunnel.	Heavily precompressed clays with a plasticity index in excess of about 30; sedimentary formations containing layers of anhydrite.
7	Cohesive Running	The removal of the lateral support on any surface rising at an angle of more that about 34° to the horizontal is followed by a "run", whereby the material flows like granulated sugar until the slope angle becomes equal to about 34°. If the "run" is preceded by a brief period of raveling. the ground is called Cohesive Running.	Cohesive Running occurs in clean, fine, moist sand.
8	Running		Running occurs in clean, coarse or medium sand above the water table.
9	*Very Soft Squeezing	Ground advances rapidly into the tunnel in a plastic flow.	Clays and silts with high plasticity index.
10	Flowing	Flowing ground moves like a viscous liquid. It can invade the tunnel not only through the roof and the sides but also through the bottom. If the flow is not stopped, it continues until the tunnel is completely filled.	Any ground below the water table that has an effective grain size in exess of about 0.005 millimeter.
11	*Bouldery	Problems incurred in advancing shield or in forepoling; blasting or hand-mining ahead of machine possibly necessary.	Boulder glacial till; rip-rap fill; some landslide deposits; some residual soils. The matrix between boulders may be gravel, sand, silt, clay or combinations thereof.

The resulting muck consists of large pieces which are highly remolded, very sticky and hard to handle. Upon final dumping from the muck cars after transport, the muck becomes a very soft putty-like, sticky material. Quite often special muck cars with curved bottoms for side-dumping must be used to discharge the clay properly. Often the interior of the muck cars are wetted down frequently to provide a lubricant and in some cases sand coatings are placed in the muck cars to prevent the soft clay from sticking.

Individual clay particles are very small; two microns (0.00008 in.) is a commonly accepted upper limit for clay particle size. Thus, excavation of clay during tunneling affects the overall clay mass but not the individual clay particles. By physically breaking the clay into chunks the continuity and characteristics of the original deposits is completely destroyed.

One of the most useful test procedures for evaluating the performance of muck is the Atterberg limit test. Several relationships have been developed which relate the Atterberg limits to important engineering properties for both undisturbed and remolded soil conditions. The first is the liquidity index which compares the natural water content of the soil to the water contents for the liquid and plastic limits. A numerical value for the liquidity index is given by the formula shown below:

$$I_\ell = \frac{W_{nat} - P_w}{L_w - P_w}$$

Where: I_ℓ = liquidity index

W_{nat} = natural water content (%)

P_w = plastic limit (%)

L_w = liquid limit (%)

and $L_w - P_w$ = plasticity index (%)

For a liquidity index greater than one, the natural water content exceeds the liquid limit. This type of soil deposit can be expected to be soft or very soft and highly sensitive to disturbance. If the liquidity index is negative or equal to zero, the natural water content is at or below the plastic limit and the soil deposit will probably be stiff and relatively insensitive. The unconfined compressive strength for undisturbed clays with a liquidity index near zero may vary from 1.0 to as much as 5.0 tsf [4-2].

The liquidity index is also qualitatively indicative of fine-grained soil compressibility. Soils with a liquidity index at or above one will be much more compressible in general than those with a liquidity index at or below zero. An example of such a relationship is given in Figure 4-5 where the measured excess preconsolidation

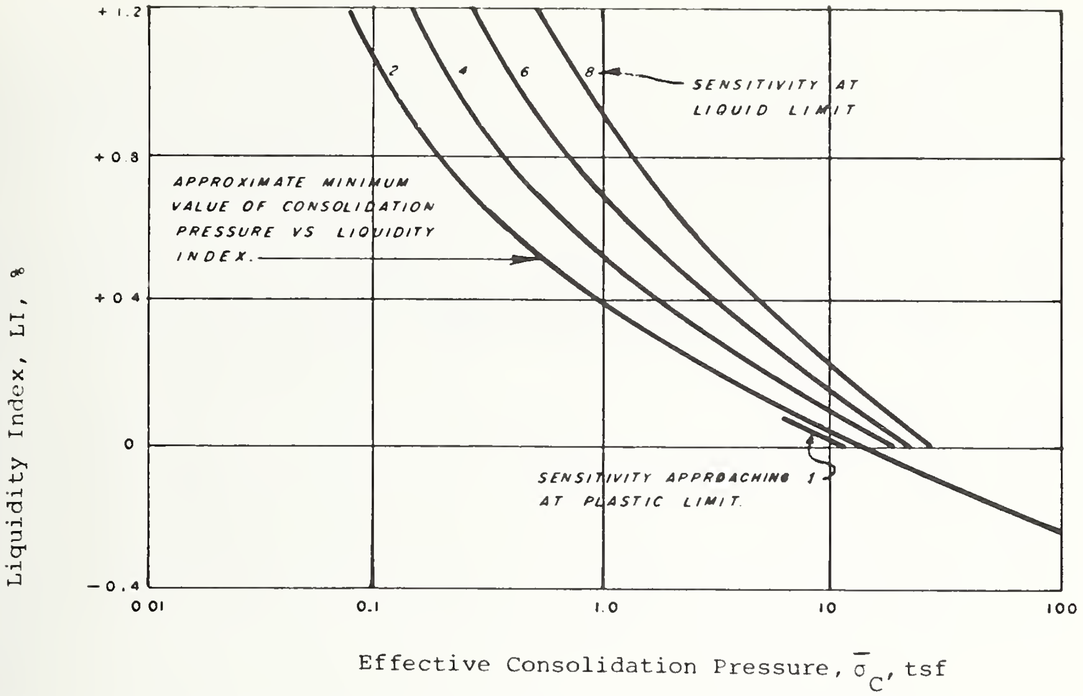


FIGURE 4-5. LIQUIDITY INDEX VERSUS EFFECTIVE CONSOLIDATION PRESSURE [4-9]

SOURCE: NAVDOCKS DM-7; p. 7-3-8

pressure of undisturbed soils is given as a function of the liquidity index and soil sensitivity [4-9]. The greater the "effective consolidation pressure," the less compressible is the soil. Although disturbance during excavation will disrupt the relationships shown in this diagram, a similar relationship could probably be derived for tunnel muck.

Additional strength relationships as a function of the plasticity index are provided in Figure 4-6. Figure 4-6a shows the angle of internal friction for drained clay specimens; Figure 4-6b shows the ratio of undrained shear strength to effective vertical overburden stress.

A widely accepted relationship between the compression index of undisturbed clay soils, C_C, and the liquid limit is given by the following formula [4-9]:

$$C_C = 0.007\ (L_W - 10\%)$$

This formula could be used directly to estimate the compression index for a disturbed clay deposit such as muck. Test results on undisturbed samples indicate that the undisturbed compression index is approximately 30 percent greater than the disturbed value [4-2].

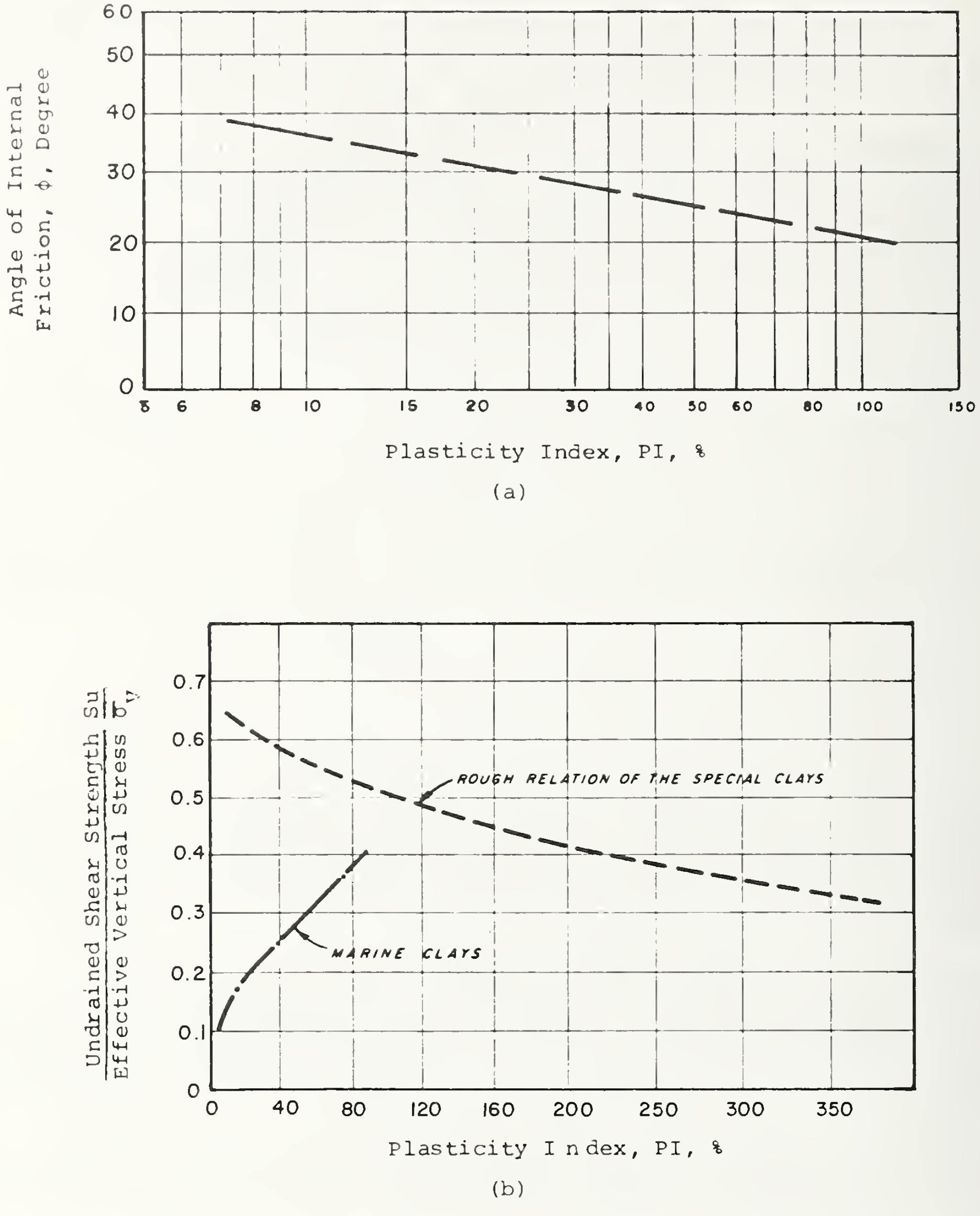


FIGURE 4-6. STRENGTH PARAMETERS VERSUS PLASTICITY INDEX FOR NORMALLY CONSOLIDATED CLAYS [4-10]

SOURCE: LAMBE & WHITMAN; p. 452

It is interesting to note that the compression index actually increases for the undisturbed clay specimen. This indicates that a clay deposit which is remolded and then compacted into place as a landfill will usually experience less compression than the virgin consolidation of the in-situ deposit.

A relationship between the liquid limit and the coefficient of consolidation (c_v) is shown in Figure 4.7. This diagram reveals that the coefficient of consolidation decreases as the liquid limit increases and as the soil is remolded. Hence, tunnel muck will take longer to consolidate than the undisturbed deposit.

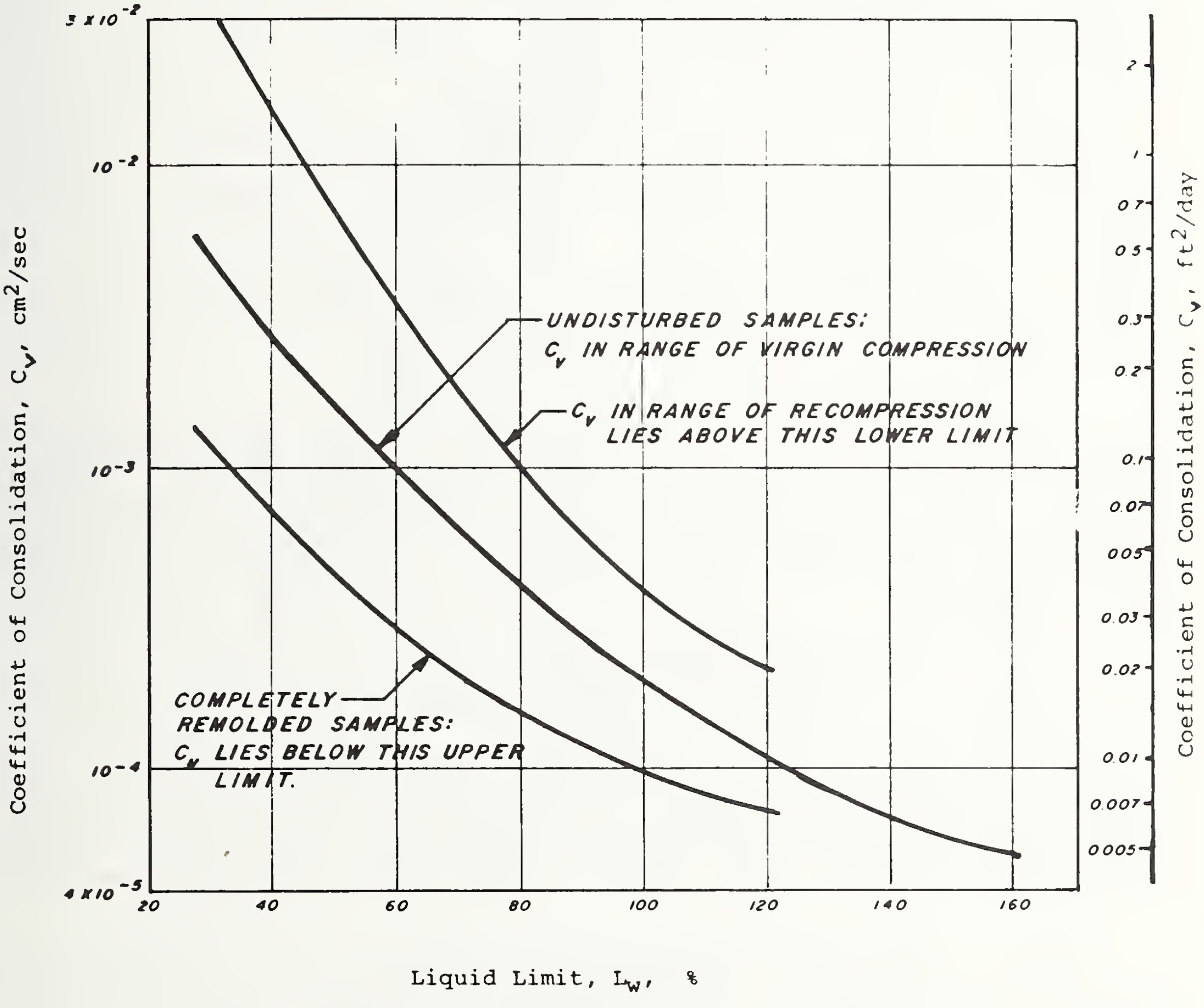


FIGURE 4-7. COEFFICIENT OF CONSOLIDATION VERSUS LIQUID LIMIT [4-9]

SOURCE: NAVDOCKS DM-3; p. 7-3-14

The engineering properties of clay-based muck can thus be determined by using semi-empirical relationships developed for clay or by adjusting undisturbed test data for the effects of disturbance. Field and laboratory tests can be combined, for instance, to evaluate the disturbed shear strength. Field vane tests can provide data on the "sensitivity" of the deposit. The strength determined by unconfined compression tests on undisturbed laboratory tests can then be reduced according to the field vane test data.

4.2.3.2 Sand and Gravel-based Muck

Miners typically describe sand and gravel deposits as wet, moist or dry. A tunnel driven under the water table is typically wet. However, if the tunnel is driven in compressed air the deposit will have the same characteristics as a moist material since most of the free water is expelled from the voids during the mining operation. And if the material is handled promptly onto a conveyor, the resulting muck is usually a high quality, slightly moist material. Extremely wet deposits may be encountered where dewatering techniques supplemented by internal tunnel dewatering by diaphragm pumps are used to lower the water table. Generally this material will be heavy, wet and hard to handle. However, subsequent aeration can reduce the moisture content to an acceptable level for controlled-fill use. Dry sands and gravels mine very easily and, if the material contains a high percentage of uniform sizes, the face can "run".

Particles are usually composed of resistant minerals, and the grain size distribution of the deposit will not change appreciably during excavation. If anything, the deposit will be more coarsely textured than was expected due to the inability to sample large particles with ordinary test borings. It is possible to estimate permeability and frost susceptibility from the results of the grain size distribution tests which are usually performed on samples from test borings.

Figure 4-8 shows a relationship between the effective diameter and coefficient of permeability for recompacted granular soils [4-9].

Uniform soils are not frost susceptible unless the grains are smaller than 0.001 mm. Relatively uniform soils become frost susceptible if at least 10 percent of their grains are less than 0.02 mm. Well-graded or mixed-grain soils become frost susceptible if grains smaller than 0.02 mm. constitute 3 percent of the total aggregate [4-2].

The most significant change which occurs for a sand and gravel deposit is a reduction in strength during excavation. Most deposits possess some degree of cementation between particles which contributes to their in-situ strength. This cementation is destroyed by disturbance during excavation, but recompaction, such as in a landfill, will create a mass which will be stable for most engineering uses. Therefore, the loss of cementation is not a serious consideration. In many cases, the strength due to in-situ

SOURCE: NAVDOCKS DM-7; P. 7-3-10

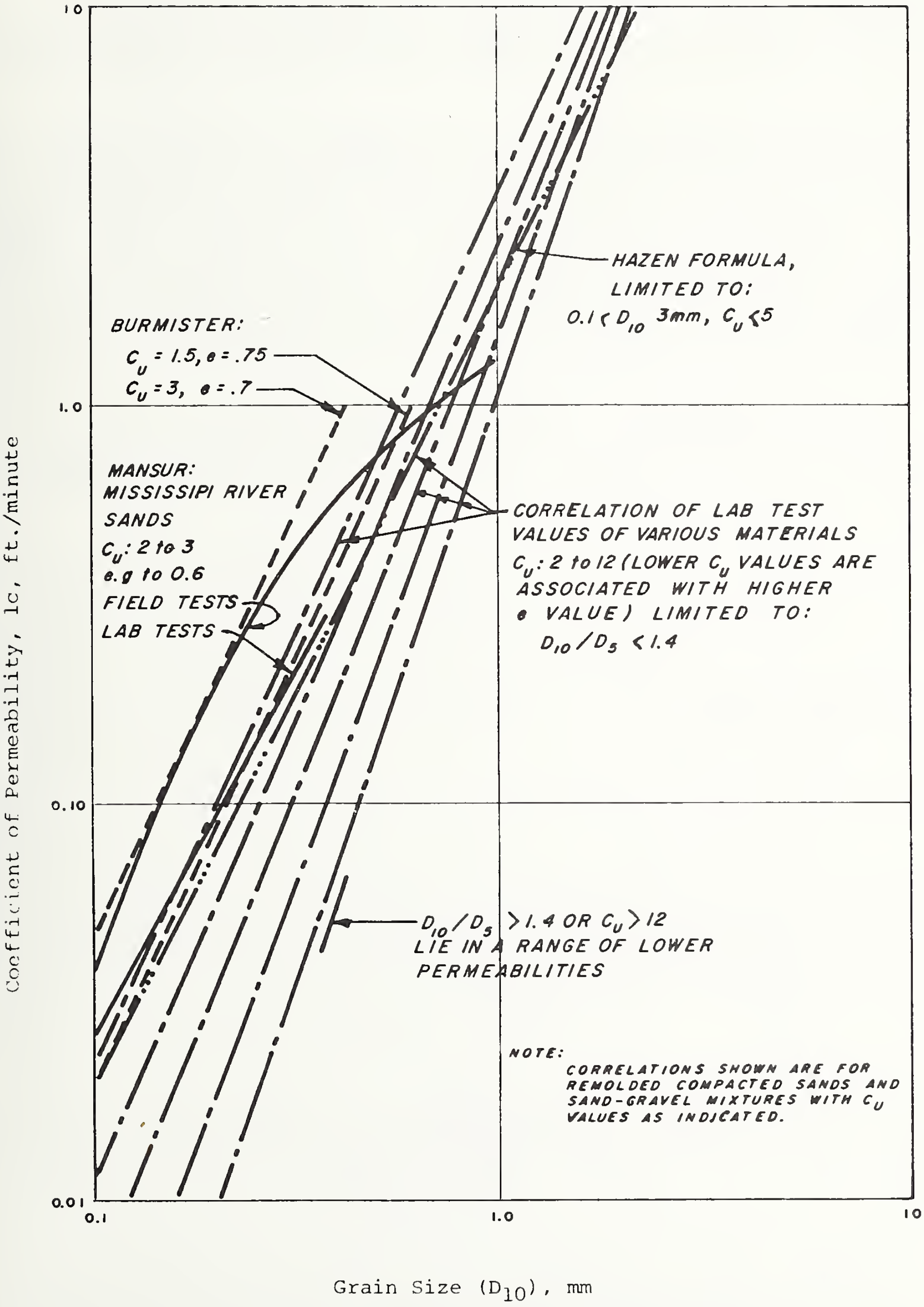


FIGURE 4-8. PERMEABILITY OF SANDS AND SAND-GRAVEL MIXTURES [4-9]

cementation will be replaced by particle interlocking after compaction. Friction angles used to measure strengths (Section 4.2.2) can also be used to estimate the strength of recompacted sand deposits.

The compressibility of sand and gravel is related to the gradation, relative density, and mineral composition of the sample. Within the same natural deposit, the in-situ density can vary from loose to dense, resulting in a wide variance in the settlement of structures. Values of elastic properties, such as the secant modulus, have been measured in the laboratory on recompacted samples. Typical values of the secant modulus are given in Table 4-3. The compressibility of sand muck can thus be estimated based on the gradation and final density of the recompacted material.

TABLE 4-3. VALUES FOR SECANT MODULUS [4-1]

SOURCE: LAMBE & WHITMAN; p. 155

Soil	Relative Density	Modulus (PSI x 10^3) Vertical Stress From 9 to 15 PSI	Modulus (PSI x 10^3) Vertical Stress From 29 to 74 PSI
Uniform Gravel	0	4.4	8.7
1 mm < D < 5 mm	100	17.0	26.0
Well Graded Sand	0	2.0	3.7
0.02 mm < D < 1 mm	100	7.5	17.6
Uniform Fine Sand	0	2.1	5.1
0.07 mm < D < 0.3 mm	100	7.4	17.4
Uniform Silt	0	0.4	2.5
0.02 mm < D < 0.07 mm	100	5.1	11.1

At stress levels exceeding 1 ksi, crushing of individual particles takes place. Typical one-demensional stress-strain plots illustrating this behavior are shown in Figure 4-9. Linear stress-strain behavior is appropriate at stress levels in the normal engineering range, i.e., 0.025 to 0.100 ksi.

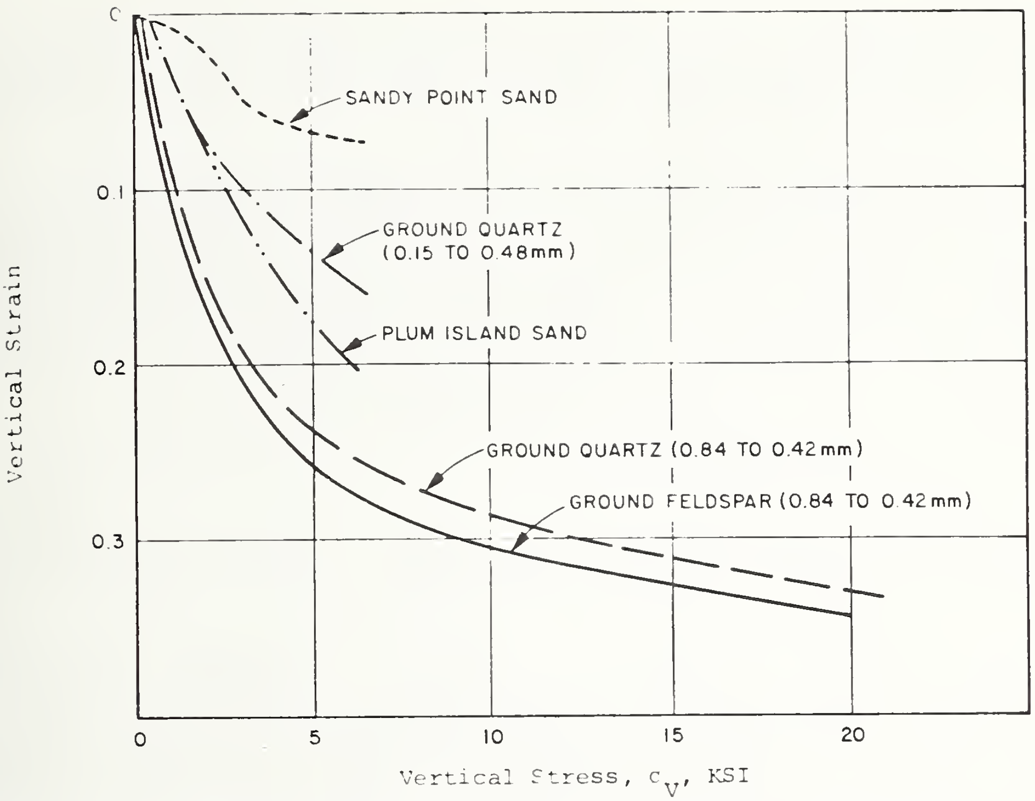


FIGURE 4-9. STRESS-STRAIN BEHAVIOR FOR SAND IN COMPRESSION [4-10]
SOURCE: LAMBE & WHITMAN

4.2.3.3 Miscellaneous Types of Soil-based Muck

Many types of soil do not fit easily into either the clay or sand and gravel-based muck described previously. The three most common examples are silt, glacial till, and highly organic material. Silt can be tested as either a clay or a sand. Glacial till is a mixed-grained soil which is hard to sample and is usually tested only for grain size distribution. Highly organic soils are not significantly valuable as engineering materials.

Silt is often defined as a fine-grained soil with little or no plasticity. It is typically a transitional material between sand and clay. Silt reacts readily to changes in water content and can become essentially fluid with a small increase in water. Its small particle size results in a low permeability that retards drainage and stabilization. Relatively small percentages of clay particles can cause silt to act as a clay.

Glacial till is described as an unstratified glacial deposit of clay, silt, sand, gravel and boulders. It is usually extremely hard and dense and difficult to mine, although stability of the deposit would generally not be a problem. Blasting is sometimes required.

Increases in water content after excavation can cause till to become fluid and unstable due to the presence of silt and clay-sized particles. Boulders can be a serious problem for a variety of different tunneling and muck handling methods.

Organic soils include peat and organic silts and clays. Peat is an aggregate of fibrous fragments of decaying vegetable matter. Its color ranges from light brown to black and it is characterized by low strength, high compressibility and high gas contents. Generally, these materials mine very well although compressed air is sometimes necessary below the water table. Peats and organic silts are usually encountered at shallow depths and the fibrous particles and plasticity provide enough stand-up time to prevent stability problems.

4.2.3.4 Rock-based Muck

Rock is mined either by tunnel boring machines or by conventional drill and blast procedures. The method of mining directly affects the type of rock muck produced.

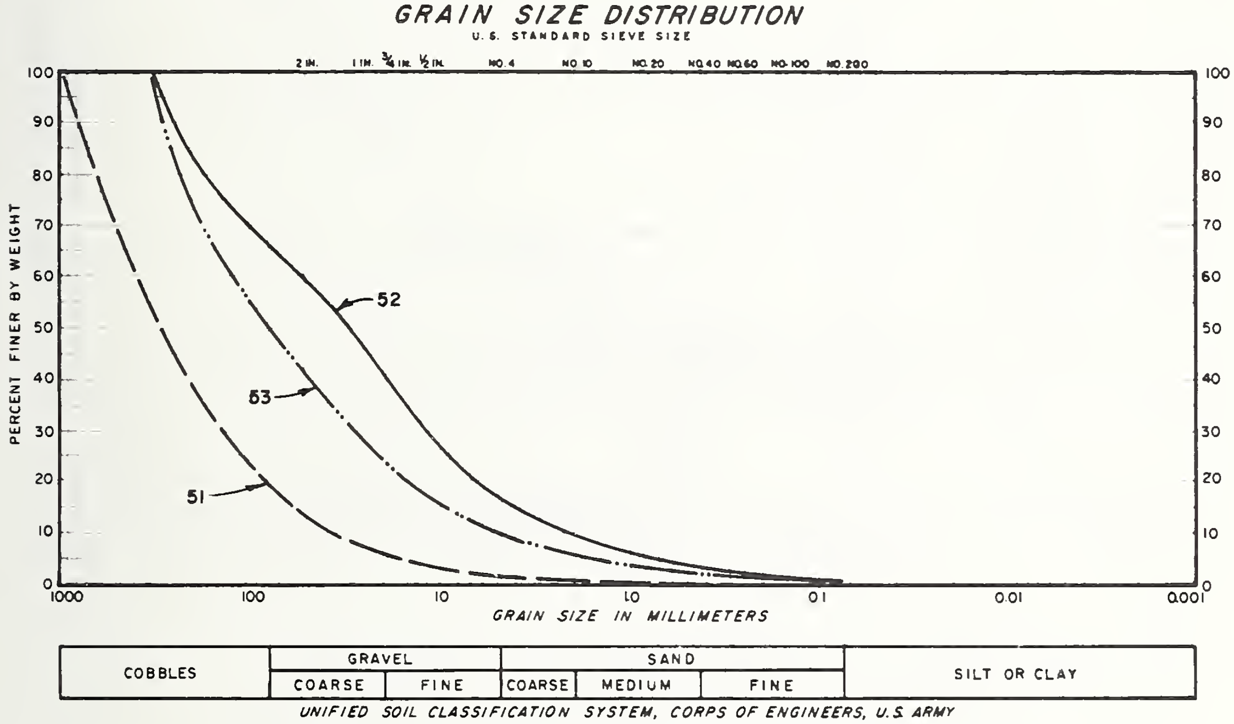
A description of TBM muck is given in Section 3.2 with typical gradation curves in Appendix B (Figures B-1 to B-11). Relationships between the unconfined compressive strength of the intact rock, which is frequently determined by current laboratory procedures, and the coefficient of uniformity of the rock muck show that well-graded materials are produced by TBMs for a wide range of rock types (Figures 3-9, 3-10).

Drill and blast muck is more coarsely textured than TBM muck and includes blocks of over 36 in. in maximum dimension down to rock flour. Some silt and clay-sized particles may occur due to weathered rock areas or fault zones within the rock mass. Although rock falls and overbreak may contribute very large pieces to the muck pile, these pieces are usually blasted again in order to fit the muck handling equipment. Typical drill and blast gradation curves are shown in Figures 4-10 through 4-12 [3-15]. Plots of unconfined compressive strength of the intact rock versus the coefficients of uniformity and curvature of the rock muck given in Figures 4-13 and 4-14, respectively, show that drill and blast procedures also produce well-graded tunnel muck for a wide range of rock types.

A very simple index test for classifying rock has been presented by Terzaghi and is reproduced in Table 4-4. Classification of rock according to this diagram may prove helpful for determining muck utilization potential. This method is promising because the suggested tests simulate the muck environment with exposure to water causing changes in various rock types.

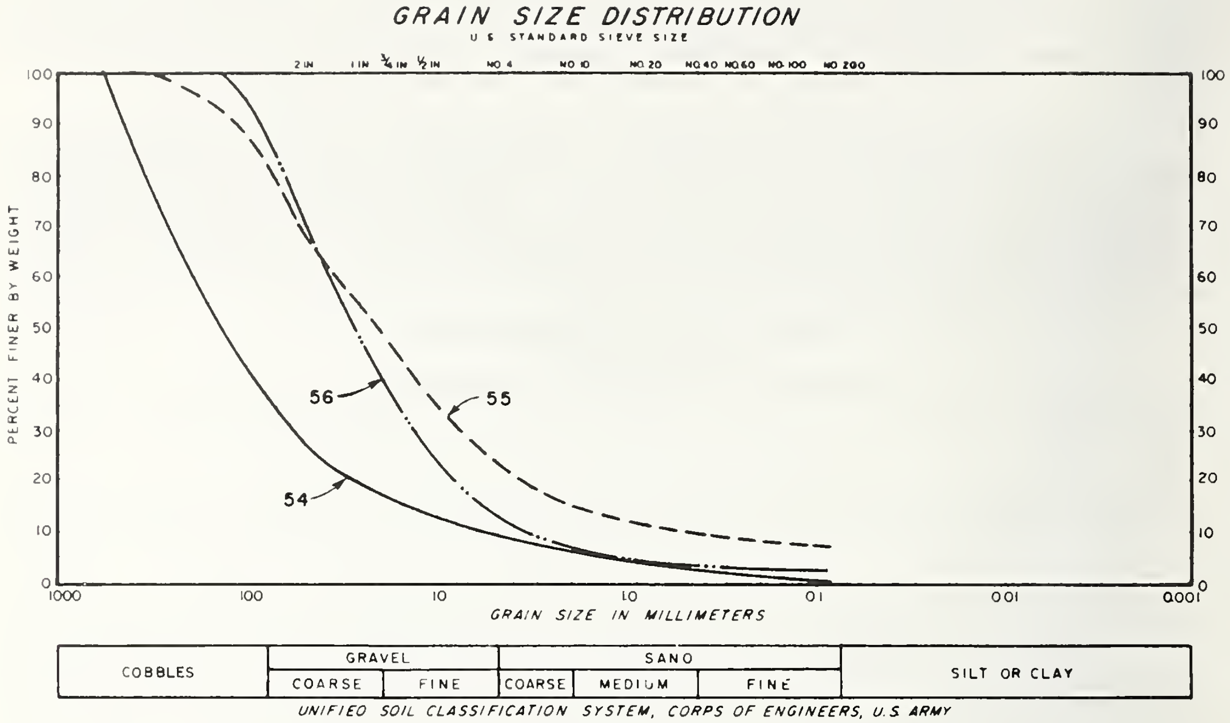
In general, rock core samples obtained from test borings are classified according to geological criteria and tested in unconfined compression. Intact rock strengths vary from 1 to 50^{+} ksi and intact tangent moduli vary from 0.5 to 15 million psi. A general rule of thumb is that the intact modulus is approximately 300 times the unconfined compressive strength [4-4]. Testing of crushed rock samples is rarely needed for design and construction purposes.

The strength of rock muck is a function of the amount of interparticle friction and interlocking. In general, it is conservative to assume that the friction angle for most rock types is equal to 30 degrees [4-12] and the angle for limestone is 35 degrees. Bearing capacity factors for compacted rock muck including a suitable factor of safety can be based on these values.



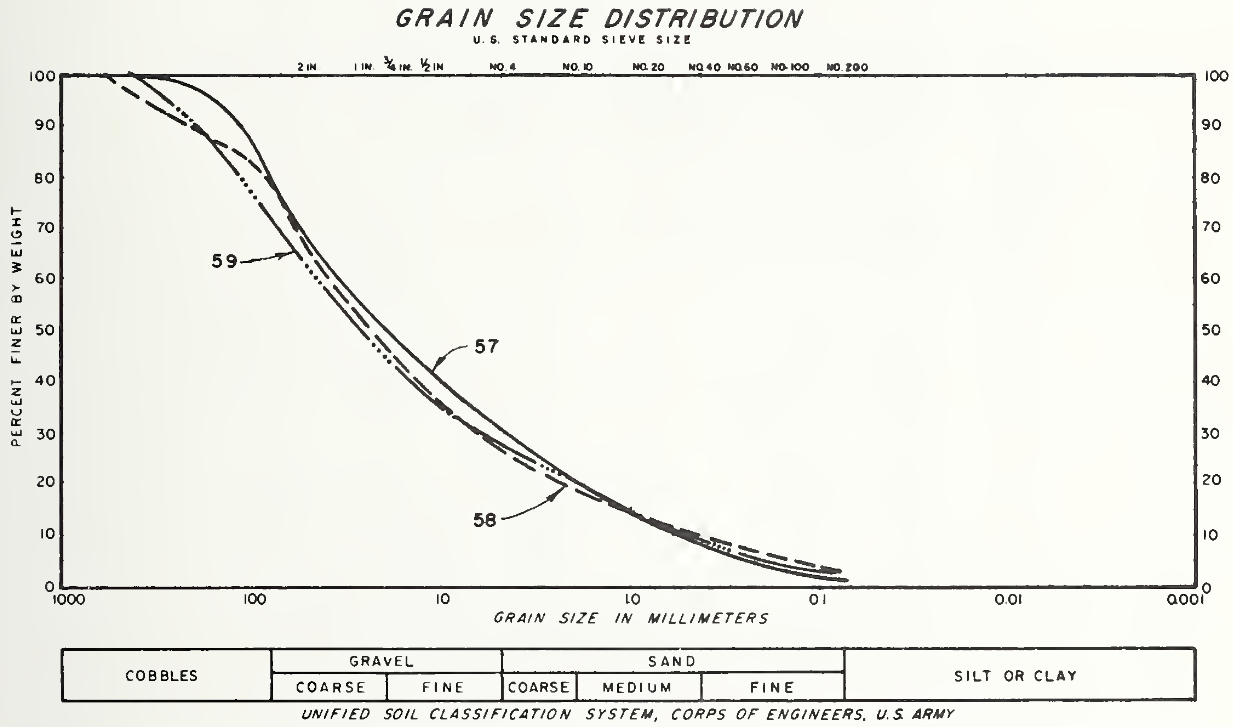
Sample No.	Description	Coefficient of Uniformity, C_U	Coefficient of Curvature, C_C
51	COBBLES	12	1.4
52	GRAVEL and COBBLES	28	1.6
53	GRAVEL with cobbles	28	1.2

FIGURE 4-10. GRADATION CURVES FOR DRILL AND BLAST MUCK - SAMPLES 51 THROUGH 53 [3-15]



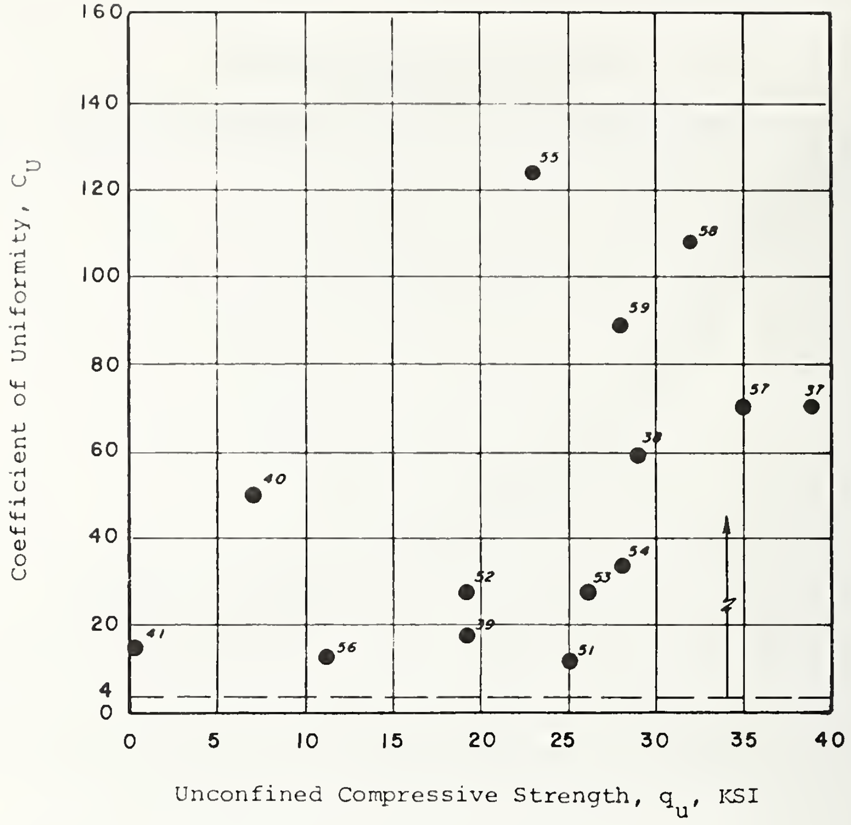
Sample No.	Description	Coefficient of Uniformity, C_U	Coefficient of Curvature, C_C
54	COBBLES and GRAVEL	33	5.8
55	GRAVEL with cobbles	12	1.2
56	GRAVEL with cobbles	13	1.4

FIGURE 4-11. GRADATION CURVES FOR DRILL AND BLAST MUCK - SAMPLES 54 THROUGH 56 [3-15]



Sample No.	Description	Coefficient of Uniformity, C_U	Coefficient of Curvature, C_D
57	sandy GRAVEL with cobbles	70	1.4
58	sandy GRAVEL with cobbles	108	2.8
59	sandy GRAVEL with cobbles	88	1.9

FIGURE 4-12. GRADATION CURVES FOR DRILL AND BLAST MUCK - SAMPLES 57 THROUGH 59 [3-15]

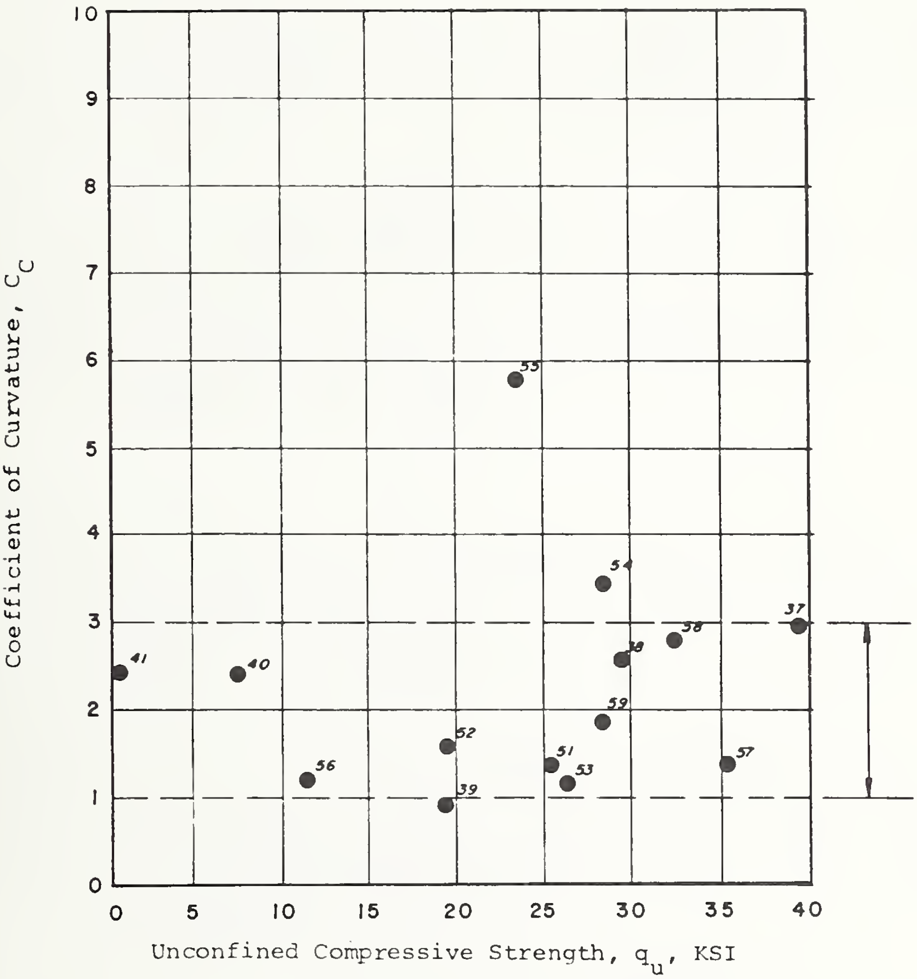


Notes: 1) $C_U = \frac{D_{60}}{D_{10}}$

2) For well graded materials $C_U > 4$

3) All data points from research by Holmes & Narver, Inc.

FIGURE 4-13. COEFFICIENT OF UNIFORMITY VERSUS UNCONFINED COMPRESSIVE STRENGTH OF INTACT ROCK FOR DRILL AND BLAST MUCK



Notes: 1) $C_C = \frac{(D_{30})^2}{D_{60} \times D_{10}}$

2) For well graded materials $1 < C_C < 3$

3) All data points from research by Holmes & Narver, Inc.

FIGURE 4-14. COEFFICIENT OF CURVATURE VERSUS UNCONFINED COMPRESSIVE STRENGTH OF INTACT ROCK FOR DRILL AND BLAST MUCK

TABLE 4-4. TERZAGHI'S GUIDE FOR DISTINGUISHING ROCK, WEATHERED ROCK, AND SOIL

In Original State	Volume Change Produced by Saturating Dried Fragments With Water	After Repeated Drying, Immersing, and Shaking, or Upon Prolonged Exposure to Atmosphere	Group
solid with ringing sound when struck by hammer	imperceptible	unchanged	solid rock
		breaks up into small hard pieces with clean surface	finely fissured or crushed unaltered rock
		breaks up into small fragments with "greasy" surfaces owing to presence of fine grained weathering products	slightly decomposed fissured rock
		breaks up into individual sand or silt particles	sandstone or mudstone w/unstable cement
	measurable	breaks up into small angular fragments without any indication of chemical alteration	intermediate between rock and clay. Rock characteristics predominating
		gradually transformed into suspension of soil particles	intermediate between rock and clay. Clay characteristics predominating
solid with dull sound when struck		gradually transformed into suspension of clay particles and a sediment consisting of angular rock fragments	thoroughly decomposed rock
solid with dull sound when struck, plastic or stiff viscous	imperceptible to important	completely transformed into a suspension and/or a loose sediment	clay, silt
slightly cohesive to cohesionless	imperceptible	rapidly loses its cohesion when agitated with water	rock powder, grit, sand, gravel

Actual testing of crushed rock samples would allow an increase in the angle of internal friction taking into account the effect of interparticle interlocking. Based on large scale triaxial tests, friction angles for crushed rock were shown to vary between 45

60 degrees with an average of 50 degrees [4-13]. As shown in Figure 4-15, friction angles decrease with increased confining stress as a result of particle crushing.

The tangent modulus or compressibility of rock muck is related to the confining stress. Examples of the modulus of elasticity for typical crushed rock materials are shown in Figure 4-16. In these cases, the initial tangent moduli varied from 10,000 to 50,000 ksi for low confining stresses.

As stated previously, rock hardness testing is becoming more common with the advent of tunnel boring machines [4-6]. Unfortunately, these tests are not the same hardness tests used by aggregate producers to evaluate materials for use with portland cement or bitiminous concrete. With time it may be possible to relate the various index test results. For the present, it is necessary to conduct additional tests as described in the following Section 4.3.2.2.

4.2.3.5 Debris

The most common types of debris are discarded equipment, wood, steel and concrete. It is surprising how much valuable equipment ends up in the muck pile. Difficult working conditions and a desire for a rapid rate of advance cause tools to be damaged, and tools which malfunction are immediately discarded and replaced. These include hand tools such as hammers, wrenches, axes and shovels, and larger items such as step ladders and scaffolding.

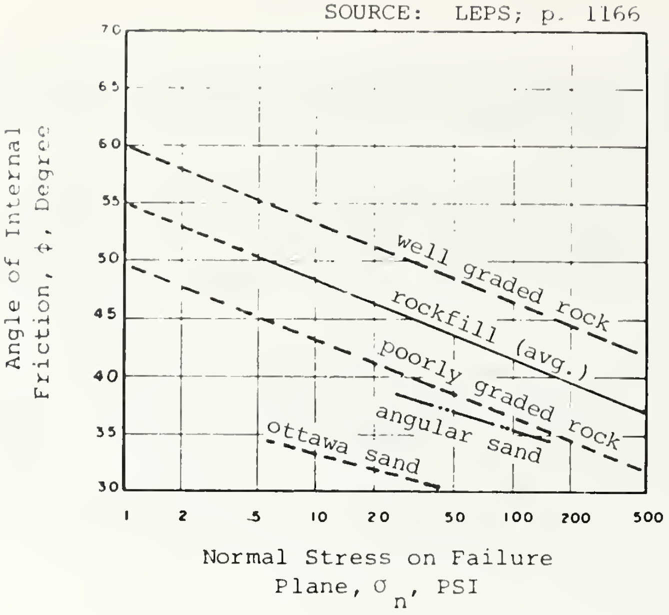
Debris is added to the muck in two different ways as construction proceeds. Some debris ends up in the muck on a continuous day-to-day basis as activities proceed at the face. It is very common, however, for contractors to set aside a day either on a regular basis or when there is a lull in the work to clean up the working area. At this time, loose, wet soil, rock and debris are removed from the tunnel invert and disposed of as muck.

Building demolition, which very often accompanies tunnel construction, also contributes to debris. Most demolition is performed under a contract separate from the actual construction of the tunnel. Tunnels constructed in large urban areas by cut and cover methods almost always encounter a layer of fill or debris which is the result of previous construction or demolition activities at the site.

In rock tunnels excavated by the drill and blast method, one is apt to find bits of broken steel, used drill bits, plastic containers for explosives, timber used for support, discarded rubber gear, paper containers such as cardboard boxes used to transport explosives, and various types of contaminated liquids such as fuel oil, hydraulic oil, etc.

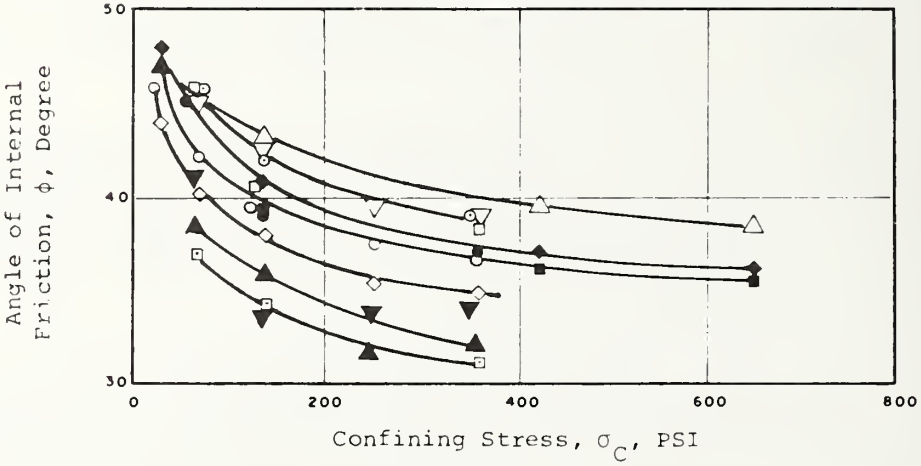
Wood is used in tunnels primarily for support and for forming. In soft ground tunnels, wood is very often used as lagging between steel ribs and the rock to hold the rock in place. Pieces of wood

SOURCE: LEPS; p. 1166



[4-13]

SOURCE: MARACHI; p. 110

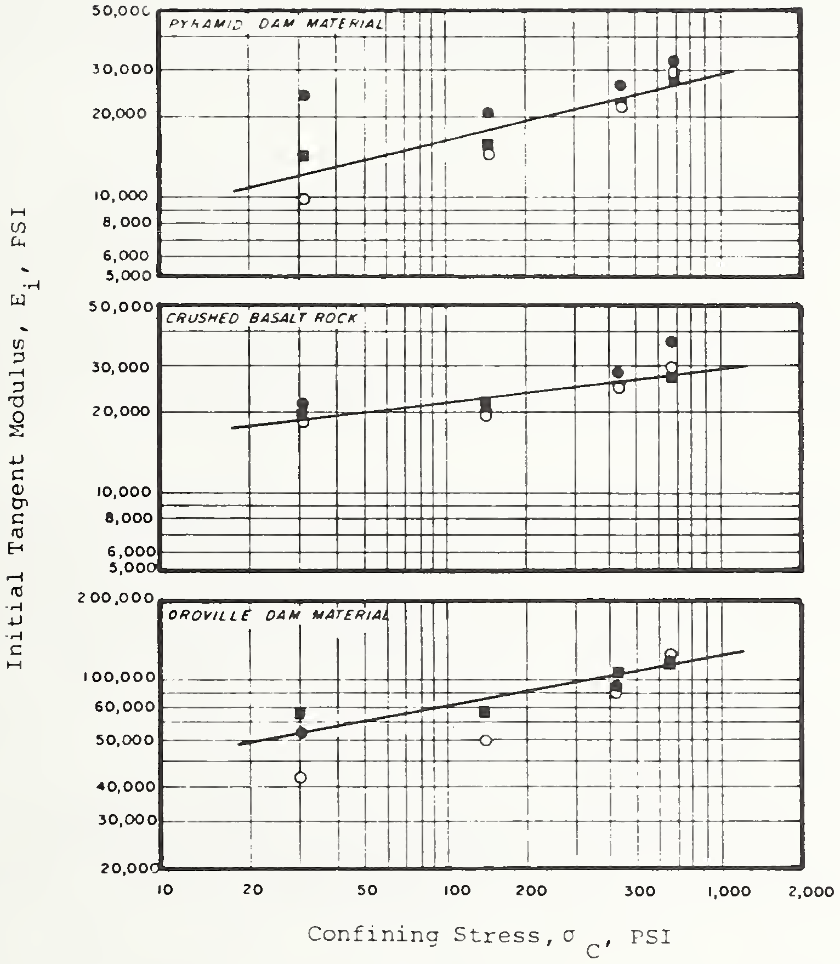


[4-14]

Legend

Symbol	Dam or Place	Symbol	Dam or Place
△	Oroville	■	Pyramid
▽	Pinzandaran	◇	El Infiernillo
⊙	San Francisco	▼	El Granero
□	San Francisco	▲	El Granero
◆	San Francisco	⊡	Mica
●	Mal Paso	not shown	Mica
○	El Infiernillo		

FIGURE 4-15. ANGLE OF INTERNAL FRICTION VERSUS STRESS FOR BLAST ROCK



Legend

Symbol	Specimen Diameter	Maximum Particle Size
■	36 in.	6 in.
○	12 in.	2 in.
●	2.8 in.	.45 in.

FIGURE 4-16. TANGENT MODULUS VERSUS CONFINING STRESS FOR BLAST ROCK [4-14]

SOURCE: MARACHI; p. 109

cut off to form the liner and excess wood used in concrete forms end up in the muck pile.

Concrete debris is produced when concrete bulkheads are removed. When excess grout or wet concrete spills on to the invert of the tunnel, it is shoveled into the muck pile. Normally, the percentage of concrete debris is not significant but when shotcrete is applied, the rebound will regularly contaminate the muck.

4.3 INVESTIGATING THE POTENTIAL FOR MUCK UTILIZATION

Data obtained from subsurface and laboratory tests discussed in Section 4.2 provide the bulk of the information necessary to evaluate the potential for muck utilization. Some additional field exploration and laboratory testing is desirable, however, in order to improve planning and reduce contingencies for a program of muck utilization. Frequently the additional data for muck utilization will also be useful for design and construction.

The scope of additional testing for muck depends in part on the arrangements made for its utilization. In general, the test procedures outlined below are intended to be used in conjunction with the currently available data to assist the owner or tunnel contractor with plans for muck utilization. It is assumed, as recommended later in this report, that utilization plans will be flexible so that changes in the character of the muck can be dealt with.

4.3.1 Field Exploration

As discussed below, a few of the recommended laboratory tests for muck utilization planning require large specimens. Large soil specimens are also desirable to accurately determine the grain size distribution of the entire deposit, rather than that of small samples obtained in test borings. For these reasons it is recommended that large diameter or even accessible explorations be made. For this report, a large sample is defined as at least 30 lb of soil or rock material. By comparison, a standard split spoon sample, driven 18 in., recovers about 1 lb of soil.

It is realized that accessible explorations are expensive, especially in urban areas. In general, they should be made when the design phase test boring program and final route selection are complete and a very deliberate sampling procedure is possible. A program of "purposeful sampling" is described in the literature [4-15] as a process for obtaining a maximum amount of subsurface information for the least possible cost. For example, if a proposed tunnel is located in rock, it would be possible to auger through the overburden without sampling in order to obtain rock specimens for testing.

One of the best types of exploration for obtaining large samples is in fact, augering. Augers up to several feet in diameter are readily available in many sections of the country for use in caisson or pier type foundation construction. Excavations more than 2.5 ft in diameter can be easily entered by an inspector if it can be done safely. Otherwise when the excavation reaches a critical location, a small clamshell device could be used to obtain large samples. A complete record of the entire excavation could be kept with a realization that it is difficult to establish precise sampling depths during continuous augering.

With respect to samples, it is recommended that additional soil samples be saved for laboratory testing. In general, about 25 percent of the sample from a split spoon sampler is placed in a sample jar and the rest is wasted. Saving all the material at selected locations would satisfy some of the requirements for large sample testing.

The only additional field test that is recommended is the field vane test for clay soils. Although these tests are already done in many cases for design and construction purposes, their increased use for estimating clay sensitivity is recommended.

For large sample rock testing, it is recommended that a few carefully selected additional rock core borings be performed. It is not necessary to make large diameter holes in this case unless it is intended to provide a pilot shaft or tunnel for inspection by designers and contractors. Regular NX borings could be drilled, carefully logged, and photographed, and then all the rock core could be made available for muck utilization testing.

Additional test borings can be completed at a small increase in exploration cost, particularly if "purposeful sampling methods" are used. Standard NX core borings can be completed and the samples provided for destructive laboratory testing. Because of the destructive testing, these samples would not be available for inspection by contractors evaluating soil conditions along the route. However, core descriptions and photographs can be provided in lieu of the actual core.

4.3.2 Laboratory Testing

As discussed in Section 5, it is possible to utilize tunnel muck as an engineering material such as landfill or concrete aggregate and in more specialized ways as a raw material ingredient for bricks or portland cement. Discussed herein are the additional test procedures which can be conducted in laboratory facilities commonly used for civil engineering purposes. Highly specialized tests, as required for brick or cement manufacture must be performed by experts in the industry which intends to use the muck. These acceptability tests would be completed at little or no cost to the owner.

4.3.2.1 Soil Testing

In general, clay-and sand and gravel-based muck are well described by standard laboratory tests currently in use. Determination of natural water content, Atterberg limits, unconfined compressive strength, compression characteristics, particle shape and gradation as discussed previously allow the engineering behavior of the remolded material to be estimated. The biggest variable would be the amount of water which will be added during excavation and delivery of the muck. Water is not easily removed from clay muck because of its low permeability. Some allowance should be made for additional drying time or consolidation due to water accumulation in fine-grained muck.

It is recommended that a series of consolidation tests be performed on thoroughly remolded samples of fine-grained soils to determine the effect of remolding on the compression index and coefficient of consolidation. For maximum benefit, it is suggested that remolded samples be obtained immediately adjacent to other samples which were tested in a relatively undisturbed state. It might also be possible to increase the water content of clay samples by a few percent during remolding to test the effect of water accumulation on clay-based muck.

The frequent use of soil in compacted landfill projects requires a knowledge of the material's moisture-density relationship and maximum dry unit weight. The relationship can be determined by the test for moisture-density relationship of soils (ASTM D1557 or D698). In this test the soil is compacted in several layers with a free falling hammer at various moisture contents to obtain a relationship between dry unit weight and moisture content. The optimum moisture content corresponds to the maximum dry unit weight. Some free-draining, cohesionless soils will not produce a well defined moisture-density curve when subjected to impact compaction. For these soils the maximum density should be determined as outlined in the test for relative density of cohesionless soil (ASTM D2049). This method utilizes vibratory compaction to obtain the maximum density, and pouring techniques to obtain the minimum density. A drawback of the moisture-density tests is the necessity for large samples. About 30 lb of soil are required to complete the moisture-density test, much more than can be obtained from a standard test boring.

In order to obtain some idea of the density relationship it is possible to use the Harvard miniature test which requires less than 5 lb of soil [4-16]. This amount can be obtained by saving more of the standard split spoon sample.

A problem of increasing concern to many engineers is the possibility of liquefaction of loose fine sand soils during earthquakes. Liquefaction is a term used to describe a group of phenomena occurring in saturated, cohesionless granular soil which is subjected to cyclic loading. Liquefaction produces a large decrease in effective stress accompanied by large deformations of the soil mass. If tunnel muck, consisting of cohesionless granular soil, is to be placed in a saturated environment and subjected to cyclic loads, the potential for liquefaction should be investigated. Criteria for liquefaction potential are developed in the laboratory by testing saturated cohesionless granular soils at varying densities under static and cyclic loading conditions. The most common type of test used is the cyclic loading triaxial test in which a cyclic load is applied to an isotropically consolidated specimen, and the stress, pore pressure, and number of cycles to failure are measured and recorded. Parametric curves developed from laboratory data are used to evaluate liquefaction potential. Split spoon samples supply the necessary volume of soil for testing.

A series of standard acceptability tests has been developed to evaluate the suitability of sand and gravel for use as concrete aggregate. The tests are used to evaluate properties such as specific gravity, soundness, scratch hardness, loss by abrasion, reactivity, and petrographic analysis. Table 4-5 contains a list of the standard tests, including the ASTM reference number, and an indication of the size of the sample required for testing.

The volume of sample required depends on the maximum particle or aggregate size. For example, for 1/2-in. aggregate, a 5-lb sample is specified, whereas 25 to 50 lb or more are required for 2-and 3-in. aggregrate. The 5-lb samples can be obtained from several split spoon samples retrieved from the same strata. However, test pits, test shafts, or large auger explorations are usually required to supply large sample volumes. It should be noted that large field samples are required in order to insure that a representative sample of the material is obtained. A smaller percentage of the material is actually tested. Thus, smaller field samples could be supplied to evaluate basic chemical, petrographic, abrasion and other characteristics with large samples deferred until the start of construction. At the time, the gradation information can be finalized based on tests on large volume samples.

A petrographic analysis, for example, involves an examination of the rock using a microscope or even x-ray diffraction techniques. A standard rock core sample would suffice as a laboratory sample. The test is used to determine physical properties such as coatings on particles, mineral type, particle shape, and general physical condition of the rock type. The extent of weathering of the aggregates can be evaluated.

Similarly, soundness tests are used to evaluate the potential for weathering of aggregate when used in concrete. The test procedure consists of subjecting the specimen to a specified number of cycles of immersion in a sodium or magnesium sulfate solution. The accumulation and growth of salt crystals in the pores is thought to cause disruptive forces similar to the action of freezing water.

The reactivity test measures the potential reactivity of aggregates with alkalies in portland cement concrete as indicated by the reaction between sodium hydroxide and a specified size and gradation of the crushed aggregate. The basic mineral and chemical properties can thus be determined on relatively small samples, consistant with standard test boring techniques.

TABLE 4-5. STANDARD ACCEPTABILITY TESTS FOR AGGREGATE

ASTM DESIGNATION	TEST NAME	QUANTITY OF SAMPLE Pounds
C88-73	Soundness of Aggregates by Use of Sodium Sulphate or Magnesium Sulphate	(1) fine aggregate 1± (2) coarse aggregate 3/4 to 3/8 in. 1.0± 1-1/2 to 2-1/2 in. 11
C127-73	Specific Gravity and Absorption of Coarse Aggregate	Max. Size — Sample Weight 1/2 in. — 5 2 in. — 18 3-1/2 in. — 55
C131-69	Resistance to Abrasion of Small Size Coarse Aggregate by Use of The Los Angeles Machine	11
235-68	Scratch Hardness of Coarse Aggregate Particles	Max. Size — Sample Weight 1/2 in. — 1/2 2 in. — 25
289-71	Potential Reactivity of Aggregates TEST NAME	> 1 lb
295-65	Petrographic Examination of Aggregates for Concrete	per D - 75
D - 75	Sampling Aggregates for Gradation Analysis Only	Fine Aggregate 25 Coarse Aggregate: Max. Size — Sample Weight 3/8 to 3-1/2 in.

The aggregate acceptability tests are standard tests which can be conducted by a concrete testing laboratory at the request of the transit authority. Alternatively, samples can be supplied to a prospective aggregate customer for testing at his facility.

Groundwater quality should also be investigated in areas where industrial wastes or other pollutants may be present. Water quality directly affects the acceptability of sand and gravel as aggregate. Water samples can be obtained during the standard test boring program and tested for pH, sulphates, chlorides, carbonates, hydrocarbons (gas, oil), etc. Water samples can be obtained by pumping at the test boring location or by recovering the pore water contained in the soil samples. Tests would be conducted by a chemical laboratory agency.

4.3.2.2 Rock Testing

Like sand and gravel-based muck, rock-based muck can be used directly as landfill or, after adequate processing, it can be used as aggregate. Unlike sand and gravel-based muck, it is not possible to predict the grain size distribution of the muck from an investigation of the in-situ properties of the rock mass. The same rock mass excavated by drill and blast procedures and by a TBM will have vastly different grain size characteristics.

The Muck Designation Number (MDN) is a promising technique for estimating the grain size of rock muck [4-17]. The system is based upon a predictor equation which can be used to mathematically compute a number (i.e. the muck designation number) which is related to a particular range of grain size distributions. Variables used in the predictor equation are the in-situ rock properties (e.g. compressive strength schmidt hardness, dry unit weight) and the excavation system parameters (e.g. for TBM methods: thrust, advance rate, revolutions per minute; and for drill and blast methods: powder factor, explosives, drill round). The predictor equation was developed from a statistical analysis of approximately 50 case studies. The final product of the analysis is the MDN ranging from 1 to 7. MDN 1 is associated with a large maximum particle size, and the predominant distribution is greater than the 1/2 in. size; MDN 7 is associated with a relatively small maximum particle size, and the predominant distribution is smaller than the 1/2 in. size. Intermediate numbers range in size and size distribution between these limits.

The predictor equations are shown in Table 4-6. The equation for TBM muck was used to check the gradation of the rock muck from the Case Study No. 2, Washington Metro Tunnel, Contract A6a. Pertinent rock quality data and machine characteristics are given below on page 4-39.

TABLE 4-6. MDN PREDICTOR EQUATIONS [4-17]

SOURCE: HALLER; p. 3-31, 3-34

I. Tunnel Boring Machine

$$\begin{aligned} \text{MDN} = {} & 18.312 - \text{DUW} \times 0.047 + \text{HCERQD} \times 10^{-5} \times 0.011 \\ & - \text{CLASS} \times 0.688 - \text{TEST} \times 1.934 - \text{CF/RPM} \times 0.004 \\ & - \text{THRUST} \times 0.119 - \text{KERF} \times 5.613. \end{aligned}$$

II. Drill and Blast

$$\begin{aligned} \text{MDN} = {} & 17.958 - \text{DUW} \times 0.094 - \text{HCERQD} \times 10^{-5} \times 0.097 \\ & + \text{P. RATIO} \times 4.853 + \text{CLASS} \times 1.113 \\ & + \text{WATER} \times 0.988 - \text{TEST} \times 3.798 - \text{PF} \times 0.083. \end{aligned}$$

III. Definition of Variables

Rock Quality

DUW = Dry Unit Weight (pcf)

HCERQD = Hardness (no units) x Compressive Strength (ksi) x Modulus (ksi) x RQD (%)

CLASS = Rock Classification
Igneous = 1, Metamorphic = 2, Sedimentary = 3

TEST = Resistance to Disintegration
No Disintegration = 1, Disintegration = 2

WATER = Water Occurrence
Dry = 1, Minor to Moderate = 2, Wet = 3

P. RATIO = Poisson Ratio

Excavation System Parameters

A. Tunnel Boring Machine

C/FRPM = Volume of Material Excavated/Hour/RPM (ft^3/hour/rpm)

THRUST = Machine Thrust (ksf)

KERF = Kerf Spacing (ft)

B. Drill and Blast

PF = Powder Factor (lbs/cu yd)

Rock Quality:

Rock Type = Schistos Gneiss

Compressive Strength = 9.7 ksi

Modulus of Elasticity = 6.9×10^6 ksi

Schmidt Hardness = 36

RQD = 60

Dry Unit Weight = 170 pcf

Rock Class = Metamorphic

Disintegration Resistance = No Disintegration

Excavation System Parameters:

Tunnel Diameter = 18 ft.

Machine Thrust = 3.94 ksf

RPM = 5

Advance Rate = 4 ft./hr.

Kerf Spacing = 0.20 ft.

The predictor equation for machine excavation is:

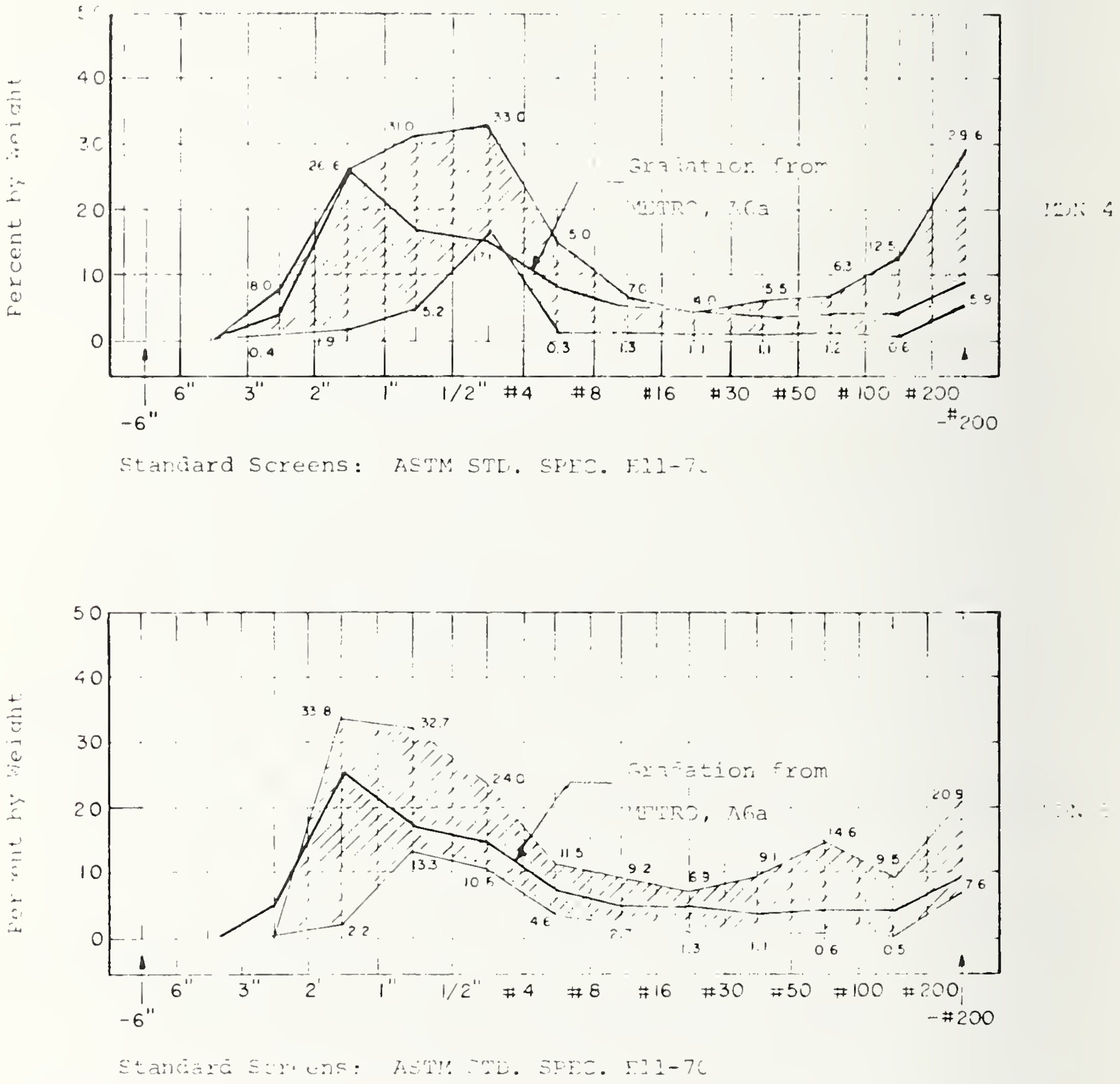
$$\begin{aligned} \mathrm{MDN} = {} & 18.312 - \mathrm{DUW} \times 0.047 + \mathrm{HCERQD} \times 10^{-5} \times 0.011 \\ & - \mathrm{CLASS} \times 0.688 - \mathrm{TEST} \times 1.934 - \mathrm{CF/RPM} \times 0.004 \\ & - \mathrm{THRUST} \times 0.199 - \mathrm{KERF} \times 5.613 \end{aligned}$$

Substituting the independent variables from above:

$$\begin{aligned} \mathrm{MDN} = {} & 18.312 - (170 \times 0.047) + (36 \times 9.7 \times 6.9 \times 60 \times 10^{-5} \times .011) \\ & - (2 \times 0.688) - (1 \times 1.934) - (254 \times (4/5) \times 0.004) \\ & - (3.94 \times 0.119) - (0.2 \times 5.613) \\ = {} & 4.6 \end{aligned}$$

Using the MDN concept, tunnel muck from this project would be assigned an MDN of either 4 or 5. The range in particle sizes and distributions for MDN 4 and 5 are plotted in Figure 4-17 together with the gradation of a sample of the TBM muck schistose gneiss from METRO Contract A6a.

The muck sample curve best fits the range assigned to MDN 5. For this example the reliability of the MDN concept is very good and the use of MDN for predicting muck particle size and distribution should be encouraged.



SOURCE: HALLER; p. 3-14, 3-15

FIGURE 4-17. MDN PLOT FOR METRO A6a ROCK MUCK [4-17]

Predicting the muck gradation will be helpful when evaluating the use of muck as an aggregate. The gradation curve will indicate how much processing would be required to satisfy the standard aggregate specifications.

Typical engineering properties of rock deposits can be estimated based on empirical correlations with geological classifications. Several empirical relationships are noted in Table 4-7. Local experience is also an important factor in assessing the rock value.

It is recommended, therefore, that the initial phase of laboratory testing on rock samples consist of geological classification combined with a gradation estimate using the MDN method. This work can be accomplished without additional laboratory testing.

If the rock shows promise as a source of aggregate, the standard acceptability tests should be completed. The acceptability tests for crushed rock aggregate are the same tests as described in Table 4-5 for natural sand and gravel aggregate. Again, note that the volume of rock actually tested is smaller than the volume required to obtain representative samples. The Los Angeles Abrasion test, for example, can be conducted on samples prepared by crushing standard NX rock core samples. Crushing is accomplished by small scale laboratory jaw crushers or other standard sample preparation equipment. A thorough geologic evaluation of the rock mass could be used to indicate the degree of reliability of the representative sample.

Strength and compressibility parameters of rockfill have been determined by laboratory tests on very large test specimens [4-13, 4-14, 4-19, 4-20]. Triaxial test specimens are prepared in cylinders typically 2 to 3 ft in diameter and 4 to 6 ft high. Smaller samples, about 3 in. in diameter and 6 in. high have been used to test TBM rock muck as described in Section 3 of this report. However, very few laboratories are equipped to handle the large scale tests required for crushed rock samples. It is recommended, therefore, that estimates of the strength and compressibility of crushed rock samples be determined by comparison with typical friction angle and modulus data as presented in Figures 4-15 and 4-16 respectively.

The potential value of rock as a mineral source can be evaluated based on a geologic and petrographic analysis of typical samples. Some of the basic industrial minerals and products extracted from minerals are listed in Tables 4-8 and 49 respectively. It is unlikely that urban transit tunnels will encounter economically significant mineral deposits. For example, a study of the northest corridor (between Washington DC and New York City) concluded that only occasional deposits of asbestos and mica would be encountered in tunnel excavations. Even if a quantity of mineral were encountered, the economics of transporting and refining the rock muck would be economically prohibitive [4-22]. It is very unlikely, therefore, that tunnel muck will be utilized as a source for industrial or rare minerals.

TABLE 4-7. TYPICAL ENGINEERING PROPERTIES OF ROCK [4-18]

SOURCE: WOOLFE

I. Summary of Engineering Properties of Rocks

Type of Rock	Mechanical Strength	Durability	Chemical Stability	Surface Characteristics	Presence of Undesirable Impurities	Crushed Shape
Igneous:						
Granite, syenite, diorite	Good	Good	Good	Good	Possible	Good
Felsite	Good	Good	Questionable	Fair	Possible	Fair
Basalt, diabase, gabbro	Good	Good	Good	Good	Seldom	Fair
Peridotite	Good	Fair	Questionable	Good	Possible	Good
Sedimentary:						
Limestone, dolomite	Good	Fair	Good	Good	Possible	Good
Sandstone	Fair	Fair	Good	Good	Seldom	Good
Chert	Good	Poor	Poor	Fair	Likely	Poor
Conglomerate, breccia	Fair	Fair	Good	Good	Seldom	Fair
Shale	Poor	Poor		Good	Possible	Fair to Poor
Metamorphic:						
Gneiss, schist	Good	Good	Good	Good	Seldom	Good to Poor
Quartzite	Good	Good	Good	Good	Seldom	Fair
Marble	Fair	Good	Good	Good	Possible	Good
Serpentinite	Fair	Fair	Good	Fair to Poor	Possible	Fair
Amphibolite	Good	Good	Good	Good	Seldom	Fair
Slate	Good	Good	Good	Poor	Seldom	Poor

II. Average Values for Physical Properties of the Principal Types of Rock

Type of Rock	Bulk Specific Gravity	Absorption	Loss by Abrasion Deval[2]	 Los Angeles[3]	Hardness	Toughness
Igneous:		Pct.	Pct.	Pct.		
Granite	2.65	0.3	4.3	38	18	9
Syenite	2.74	.4	4.1	24	18	14
Diorite	2.92	.3	3.1	--	18	15
Gabbro	2.96	.3	3.0	18	18	14
Periodotite	3.31	.3	4.1	--	15	9
Felsite	2.66	.8	3.8	18	18	17
Basalt	2.86	.5	3.1	14	17	19
Diabase	2.96	.3	2.6	18	18	20
Sedimentary:						
Limestone	2.66	.9	5.7	26	14	8
Dolomite	2.70	1.1	5.5	25	14	9
Shale	1.8-2.5	---	---	--	--	-
Sandstone	2.54	1.8	7.0	38	15	11
Chert	2.50	1.6	8.5	26	19	12
Conglomerate	2.68	1.2	10.0	--	16	8
Breccia	2.57	1.8	6.4	--	17	11
Metamorphic:						
Gneiss	2.74	.3	5.9	45	18	9
Schist	2.85	.4	5.5	38	17	12
Amphibolite	3.02	.4	3.9	35	16	14
Slate	2.74	.5	4.7	20	15	18
Quartzite	2.69	.3	3.3	28	19	16
Marble	2.63	.2	6.3	47	13	6
Serpentinite	2.62	.9	6.3	19	15	14

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[1] After immersion in water at atmospheric temperature and pressure.
[2] AASHD Method T3
[3] AASHO Method T96
[4] Dorry hardness test, U.S. Department of Agriculture Bulletin No. 949
[5] AASHO Method T5

TABLE 4-8. USES OF MINERALS IN THEIR NATURAL STATE [4-21]

SOURCE: PEELE

ABRASIVES. Quartz, garnet, opal (tripolite and diatomaceous earth), corundum and energy, diamond (bort), orthoclase. Leucite and alunite rocks have been used as millstones.

BUILDING STONES. Quartz, orthoclase, plagioclase, muscovite, biotite, pyroxene and amphibole in varying proportions, forming agneous rocks commercially known as granite and trap; talc and pyrophyllite (soapstones), serpentines, calcite and dolomite (limestones and marbles), quartz (sandstone).

ELECTRICAL INSULATORS. Muscovite, phlorgopite, calcite (marble), andalusite, kyanite, sillimanite, and dumortierite.

FERTILIZERS. Carnallite and kainite for potash; soda nitre for nitrogen; gypsum and calcite for lime; apatite (phosphate rock) for phosphoric acid. Muscovite and biotite as retainers of moisture.

FLUXES. Calcite, fluorite, borax, pyrolusite.

GLASS. Chiefly quartz (sand and sandstone) and calcite (limestone); to a less extend orthoclase, plagioclase, cryolite, and pyrolusite.

LUBRICANTS. Graphite, talc, muscovite.

PAINTS AND PIGMENTS. Hematite and limonite as "metallic paint"; the same minerals associated with clay, "ocher." Calcite (chalk) as "whiting"; wad, barite, gypsum, asbestos, muscovite, talc, kaolin, quartz, magnesite, azurite, graphite, asphaltum, rutile.

PAPER MANUFACTURE. Talc (fibrous), gypsum (selenite), as constituents of sheets. Barite, calcite, kaolin, magnesite, bauxite, muscovite, for weight and glaze.

PORCELAIN, POTTERY, ETC. Kaolin and other clays, quartz, orthoclase, albite, halite, gypsum and pyrophyllite.

PRECIOUS STONES. Diamond, beryl, emerald, corundum (sapphire and ruby), chrysoberyl (alexandrite), garnet (demantoid), spinel (ruby spinel). Semi-precious stones. Other varieties of beryl, corundum, chrysoberyl, spinel, and garnet. Also opal, chrysolite (peridot), quartz (amethyst and yellow), topaz, tourmaline, turquoize, zircon, spodumene (kunzite, hiddenite), orthoclase (moonstone). Ornamental stones. Amber, chalcedony (onyx, carnelian, sard, agate, etc.), quartz (rose cat's eye, aventurine, smoky, etc), orthoclase (amazon stone); plagioclase (labrodorite and sunstone). Amphibole (jade), lazurite (lapis lazuli), malachite, azurite, calamine, smithsonite, chrysocolla, fluorite, gypsum (satin spar), serpentine, hematite, pyrite, rhodonite, talc. Occasional faceted stones are cut from apatite, andulausite, cassiterite, chondrodite, cyanite, pyroxene (diopside), enstatite, epidote, prehnite, staurolite, sphene and vesuvianite.

REFRACTORY MATERIALS AND HEAT INSULATORS. Asbestos, bauxite, chromite, dolomite, graphite, ilmenite, kaolin, magnesite, muscovite, opal (diatomaceous earth), serpentine (chrysotile), quartz, pyrophyllite, talc (soapstone), sillimanite, andalusite, kyanite and vermiculite.

RUBBER MANUFACTURE. Sulphur, stibnite, barite, calcite, talc, pyrophyllite.

SOAP AND WASHING POWDERS, TOILET ARTICLES. Borax, opal (diatomaceous earth), talc, quartz, magnesite, orthoclase.

SUNDRIES. Coloring or decolorizing pyrolusite, psilomelane, rutile. Condiments: halite. Explosives: nitre, sulphur. Filters: opal (tripolite). Enamels: fluorite, borax. Matches: stibnite sulphur. Optical: Quartz, calcite, fluorite, gypsum, muscovite. Pencils: graphite, talc, pyrophyllite. Pipes: sepiolite (meerschaum), succinite (amber).

TABLE 4-9. PRODUCTS EXTRACTED OR MANUFACTURED DIRECTLY FROM MINERALS [4-21]

SOURCE: PEELE

ALUMINUM from bauxite, possibly gibbsite, with cryolite as flux.
ALUNOUM '$A1_2O_2$' from bauxite.
ALUMINUM SULPHATE ANO ALUM from alunite, cryolite, bauxite, kaolin.
ANTIMONY from stibnite and its alteration products and lead ores carrying antimony.
ARSENIC from arsenopyrite and sometimes from smaltite, cobaltite, enargite, etc.
BARIUM HYOROXIOE ANO BARIUM SULPHIOE from barite.
BERYLLIUM ANO BERYLLIUM OXIOE from beryl.
BISMUTH from native bismuth, bismutite, and bismite.
BORAC ANO BORIC ACIO, from colemanite, ulexite, borax, and sassolite
BROMINE from halite (salt brine).
CADINIUM from sphalerite and smithsonite containing greenockite.
CALCIUM OXIDE (LIME) from calcite (limestone)
CALCIUM SULPHATE (HEMI-HYORATE) OR PLASTIC from gypsum.
CALCIUM SUPERPHOSPHATE from apatite.
CEMENTS from calcite and clays.
CARBONIC ACIO from magnesite and calcite.
CHLORINE from hydrochloric acid and pyrolosite, the former being derived from halite.
CHROMIUM ALLOYS, especially ferrochrome from chromite.
COBALT OXIDE AND COBALT ARSENATE (ZAFFRE) from smaltite, cobaltite, and cobaltiferous limonite.
COPPER principally from chalcocite, native copper, chalcopyrite, bornite, cuprite, malachite, and azurite, although enargite, tetrahedrite, atacamite, brochantite, chalcanthite, and chrysocolla and all sources of copper in certain districts. In addition to these the iron sulphides often carry copper which is extracted after burning for sulphuric acid.
COPPER SULPHATE from chalcopyrite.
GOLO from gold and the gold tellurides (sylvanite, calaverite, petzite), from silver and copper ore and from pyrite, arsenopyrite and pyrrhotite, and sphalerite and other sulphides or tellurides.
HYOROCHLORIC ACIO from halite.
HYDROFLURIC ACIO from fluorite and cryolite.
IOOINE from sodium iodate obtained from soda nitre.
IRIDIUM from iridosmine.
IRON from hematite, limonite, magnetite, and siderite, geothite, and turgite (commercially included with limonite), some ilmenite, and rarely risidues from the roasting of pyrites..
IRON SULPHATE (ferrous) or "copperas" from pyrite and chalcopyrite.
IRON MANGANESE ALLOY from franklinite and certain manganiferous hematites and siderites; all from pyrolusite, psilomelane, manganite and other manganese oxides.
LEAO, chiefly from galena and cerussite. Anglesite and pyromorphite sometimes occur in quantity.
LEAO SULPHATE (sublimed white lead and blue lead) from galena.
LITHIUM CARBONATE from spodumene, lepidolite, and amblygonite.
MAGNESIUM from carnallite.
MAGNESIUM CARBONATE from dolomite. Basic carbonate from kieserite.
MAGNESIUM OCIDE from magnesite, and indirectly kieserite.
MAGNESIUM CHLORIDE from carnallite.
MAGNESIUM SULPHATE (EPSOM SALTS) from kieserite and less often from magnesite and dolomite.
MANGANESE ALLOYS from pyrolusite, psilomelane and braunite, or with intermixed rhodochrome and rhodomite.
MANGANESE SALTS from pyrolusite.
MERCURY from cinnabar.
MOLYBOENUM AND AMMONIC MOLYBDATE from molybdenite.
NICKEL from pentlandite, garnierite, nickeliferous pyrrhotite, and to a less extent from milled niccolite and the cobalt minerals, cobaltite and linnacite.
NITRIC ACIO from soda-nitre and nitre.
PALLAOIUM from copper ores and platinum.
PHOSPHORUS from an impure calcium phosphate (sombrerite), or from bone ash.
PLATINUM from native platinum and sperrylite, and from some gold and copper ores.
POTASSIUM from carnallite.
POTASSIUM DICHROMATE from chromite.
POTASSIUM SULPHATE from kainite.
POTASSIUM NITRATE from soda nitre and carnallite.
RAOIUM CHLORIDE from uraninite, carnotite, and autunite.
RHOOIUM from platinum.
SCLENIUM from sulphur, chalcopyrite, and pyrite.
SILICON CARBIOE (CARBORUNOUIN) from quartz and coke.
SILICON ALLOYS (FERRO-SILICON) from quartz.
SILVER from native silver, argentite, cerargyrite, embolite, proustite, pyrargyrite, and les. important, hessite, polybasite, and iodyrite. Included in other minerals, notably, galena or cerussite, but also in copper ores, manganese ores and with gold in pyrite and arsenopyrite.
SOOIUM BORATE (BORAX) from colemanite, ulexite, sassolite, kernite, and native borax.
SOOIUM STANNATE from cassiterite.
SOOIUM SULPHATE (SALT-CAKE) from halite, and from this, caustic soda, carbonate, bicarbonate.
STRONTIUM NITRATE AND CHLORIDE from strontianite.
SULPHURIC ACID, SULPHUROUS ACIO, from native sulphur, pyrite, marcasite, chalcopyrite, sphalerite, pyrrhotite, and other sulphide ores.
TANTALUM from columbite.

TABLE 4-9. PRODUCTS EXTRACTED OR MANUFACTURED DIRECTLY FROM MINERALS [4-21] (continued)

SOURCE: PEELE

THORIUM NITRATE AND THORIUM OXIDE from monazite, thorite, thorianite.
TIN AND SODIUM STANNATE from cassiterite.
TITANIUM, TITANIUM OXIDE, AND FERRO-TITANIUM from ilmenite.
TITANIUM CARBIDE from rutile.
TUNGSTEN, FERRO-TANGSTEN, from wolfrainite and scheelite.
TUNGSTATE OF SODA from wolframite.
URANIUM YELLOW OR SODIUM DIURANATE from urainite, earnotite.
VANADIUM, AND FERRO-VANADIUM from earnotite, patronite, roscoclite, vanadinite, degeloizite.
VANADIC OXIDE from mottramite.
ZINC, "ZINC DUST", AND SINC OXIDE from sphalerite, smithsonite, and calamine; and in New Jersey, willemite and zincite.
ZINC SULPHATE from sphalerite.
ZIRCONIUM OXIDE from zircon.

4.4 COSTS ASSOCIATED WITH EXPLORATION AND TESTING

Costs associated with the supplemental field and laboratory tests will depend on several factors including the extent or thoroughness of the standard design exploration program, soil and rock conditions, and the anticipated use for the muck. If a thorough design exploration program is completed, then a minimum of supplemental tests would be required. In this minimum category, costs for supplemental tests would range from 1 to 2 percent of the standard exploration costs. Similarly, if two or three alternative uses are investigated, then testing costs will be slightly higher, about 3 to 5 percent of the design exploration costs. If, however, additional field explorations and extensive laboratory testing are completed, then the costs will become significant, ranging from 30 to 50 percent of the design program costs.

It is anticipated that the primary use for muck will fall into the landfill category where simple gradation and standard compaction test data are the only tests required. Testing costs will be in the minimum category, ranging from 1 to 2 percent of the design program costs. As the potential uses become more complex, then additional testing costs will be incurred.

Basic design exploration and testing costs were established by reviewing the programs conducted for portions of the BART and METRO transit systems and estimating the direct costs at 1974 rates for field and laboratory tests. Suggested supplemental test programs were then prepared to evaluate gravel and rock muck used for landfill and aggregate. A comparison of costs produced the percentage estimates given above. The following paragraphs summarize the cost estimates.

4.4.1 Exploration and Testing Costs for Design

Design exploration and testing costs were estimated to provide a basis for comparison of muck evaluation costs. The first project investigated was the METRO Connecticut Avenue Route, a twin tube rock tunnel which runs for about 4 miles from 12th and G Streets, N.W. to the intersection of Idaho and Connecticut Avenues, N.W. The purpose and extent of the field investigation and laboratory testing program was presented in the engineering reports prepared by Mueser, Rutledge, Wentworth and Johnson [4-23]. The project was described in Section 2 of this report.

Briefly, the field program consisted of 112 borings, about 4280 ft of wash borings, 98 undisturbed samples and 3550 ft of rock cores. Special field tests included a 66 ft deep test pit used to conduct a pump test and to obtain large volume samples for identification purposes. Menard pressuremeter tests, borehole water pressure tests, and borehole photography were also used as field tests. The laboratory program for soft ground included testing for Atterberg limits, grain size distribution, permeability, compaction, unconfined and triaxial strength, direct shear, and consolidation parameters. Compression, hardness and sonic pulse testing were completed on rock samples. The estimated costs, in 1974 dollars, for exploration and testing, excluding engineering analysis and inspection, is $225,000 or about $10,700 per 1000 ft of route.

The second project investigated was also part of the METRO system. The section consisted of the Pentagon and Benning Routes from Connecticut Avenue and Eye Street, N.W. to 36th Street and Benning Road, S.E. The system, composed of two 18 ft diameter single track soft ground tunnels, is about 6.5 miles long. The extent of the exploration and testing was reported by Mueser, Rutledge, Wentworth & Johnson [4-24]. This project was also described in Section 2 of this report.

Field explorations consisted of 160 borings measuring 11,311 ft in total length, 289 undisturbed samples, 48 observation wells and 95 ft of rock cores. Field testing included 2 full scale pumping tests and 194 falling head bore hole permeability tests. Laboratory tests were made for Atterberg limits, grain size distribution, permeability, compaction, unconfined, triaxial and direct shear strengths, and consolidation parameters. Exploration and testing costs, estimated in 1974 dollars, excluding engineering analysis and inspection, are about $240,000 or about $7,100 per 1000 ft of route.

The final project investigated was a portion of the BART system along Market Street in San Francisco between the Old Ferry Slips in the east and the intersection of Market and Valencia Streets in the west, a distance of about 2.3 miles. The results of exploration and testing are reported by Parsons-Brinkerhoff-Tudor-Bechtel [4-25]. The section along Market Street consisted of four 19 ft diameter tunnels in a rectangular pattern excavated in soft ground. Field explorations included 30 borings of about 4000 ft in total length, 506 driven samples, 232 undisturbed samples and 7 observation wells. Testing was made for Atterberg limits, specific gravity, grain size distribution, consolidation parameters and unconfined and triaxial strength. Costs for this program are estimated to be about $85,000 or about $7,100 per 1000 ft of route (again expressed in 1974 dollars and excluding engineer analysis and inspection).

4.4.2 Estimated Costs for Muck Evaluation

Suggested testing programs were prepared for soft ground and rock tunneling. The programs were categorized as minimum, moderate and extensive to provide a range of cost estimates. It was also assumed that one series of tests would be completed for each 1000 ft of tunnel. The extensive program included additional field explorations such as deep test pits as required to obtain large volume samples. The costs are summarized in Tables 4-10, 4-11 and 4-12.

The data in Table 4-12 clearly indicate that the use of muck for landfill and aggregate purposes involves minimal additional testing costs. Additional testing required to evaluate the use of muck for landfill purposes involves an expenditure of less than 2 percent of the basic program costs.

An extensive supplemental testing program may be required in order to evaluate muck properties for a critical landfill or aggregate project. The major factor influencing costs is the additional field sampling required to obtain special samples or large volume samples. If the design program is not thorough or is not coordinated with muck utilization sampling needs, then supplemental exploration costs will be prohibitively high.

TABLE 4-10. SOFT GROUND TUNNELING - SUGGESTED SUPPLEMENTAL TESTING PROGRAM FOR MUCK EVALUATION

Item	Estimated Unit Price	Number of Tests		
		Minimum	Moderate	Extensive
A. Laboratory Testing				
1. Landfill				
Gradation	$ 20	1	1	1
Compaction	$ 70	1	1	1
Strength	$ 300	-(1)	-	3
Frost Susceptibility	$ 80	-	-	1
2. Aggregate				
Petrographic	$ 100	-	1	1
Chemical	$ 50	-	1	1
Standard Test	$ 80	-	1	1
B. Field Testing				
1. Sample from Standard Borings	No Charge	1	1	-
2. Large Test Pit or Auger Sample	2000	-	-	1

Note: (1) no test required

TABLE 4-11. ROCK TUNNELING - SUGGESTED SUPPLEMENTAL TESTING PROGRAM FOR MUCK EVALUATION

Item	Estimated Unit Price	Number of Tests		
		Minimum	Moderate	Extensive
A. Laboratory Testing				
1. Landfill				
Gradation		Predict by MDN	Predict by MDN	Predict by MDN
Petrographic		1	-	
Strength	$ 400	- (1)	-	3
Frost Susceptibility	$ 80	-	-	1
2. Aggregate				
Petrographic	$ 100	-	1	1
Chemical	$ 50	-	1	1
Standard Test	$ 80	-	1	1
B. Field Testing				
1. Sample from Available Rock Core	No Charge	1	1	-
2. Additional Rock Core Sample	$ 2000	-	-	1

Notes: (1) No test required

TABLE 4-12. COMPARISON OF SUPPLEMENTAL MUCK UTILIZATION TESTING WITH DESIGN PROGRAM COSTS

Description	Cost of Supplemental Test(1)	Percent of Standard Design Cost(2)
Soft Ground Tunnels		
Minimum - Landfill	\$ 90	1-3%
Moderate - Landfill and Aggregate	\$ 320	4-6%
Extensive	\$3300	47%
Rock Tunnel		
Minimum - Landfill	\$ 100	1%
Moderate - Landfill and Aggregate	\$ 310	3%
Extensive	\$3510	35%

Notes: (1) One test series conducted per 1000 ft of tunnel

(2) Basic design costs: rock tunnel \$10,000/per 1000 ft
soft ground tunnel \$7,000/per 1000 ft

5. POTENTIAL USES OF TUNNEL MUCK

5.1 INTRODUCTION

The potential uses of tunnel muck can be divided into two major categories: (1) use of muck as a construction material and (2) use of muck as an ingredient in a specialized manufacturing process. The first category includes construction of engineered, compacted fill, controlled fill, and uncontrolled fill. The engineering classification and the nominal strength and compressibility characteristics of the basic muck types control the appropriate use of the material. The second category includes uses such as clay muck as an ingredient in fired clay products or cement, and the use of sand or rock muck as an aggregate in asphalt or bituminous concrete. The appropriate use is governed by the physical and chemical properties of the muck.

Highly specialized uses such as manufacturing glass from sand muck or production involving iron or gold ore are not considered. Even if such uses were possible, the schedule for construction would not allow time for processing, and the muck would simply be stockpiled. Stockpiling would then be the disposal method used by the tunnel contractor.

Also, as a manufacturing process becomes more involved and costly, the cost of raw materials becomes less important than the quality of the raw material. Once an involved process begins, time is crucial, and any procedure which increases the duration of a process increases the cost of the final product. The possibility of convincing a processor to use tunnel muck in an involved production scheme, even if it is provided free of charge, is remote unless that processor has some guarantee of the quality of the muck he is going to receive. The quality of tunnel muck, however, cannot be guaranteed.

The considerations used to select the potential uses of tunnel muck are consistent with the tunneling process in an urban environment. A muck utilization-suitability chart is presented in Table 5-1. The chart lists the general categories of muck utilization which are discussed in detail within this section.

5.2 UTILIZATION OF MUCK AS A CONSTRUCTION MATERIAL

The general civil engineering applications of soil and rock materials have been related to basic soil properties, such as gradation and plasticity, or to Unified Soil Classification. Some typical relationships are included in Tables 5-2, 5-3, and 5-4. The most important parameters governing the use of the material are the strength, compressibility and permeability.

TABLE 5-1. MUCK UTILIZATION - SUITABILITY CHART (1)

	Category	Rock Muck		Soft Ground Muck	
		TBM	Drill & Blast	Sand & Gravel	Clay & Silt
Construction Material	Engineered, Compacted Fill	1	2	1	3
	Controlled Fill	1	1	1	2
	Uncontrolled Fill	1	1	1	1
	Sanitary Landfill	1	3	1	2
Specialized Material (2)	Fired Clay Product	3	3	3	1
	Light Weight Aggregate	2	2	3	2
	Portland Cement	1	2	3	1
	Portland Cement Aggregate	1	1	1	3
	Bituminous Cement Aggregate	1	1	1	3
	Pavement Base Course	1	1	1	3
	Track Ballast	2	1	3	3
	Miscellaneous Rip Rap	2	1	3	3

Legend:
1 = Excellent
2 = Satisfactory
3 = Poor

Note: (1) Based on general physical gradation; suitability for specific use also governed by chemical and other tests.

(2) Excavated material must be compatible to specialized use.

TABLE 5-2. DESCRIPTION OF SOIL COMPONENTS [4-10]

SOURCE: LAMBE & WHITMAN; p. 36

Soil	Soil Component	Symbol	Grain Size Range and Description	Significant Properties
Coarse-grained Components	Boulder	None	Rounded to angular, bulky, hard, rock particle, average diameter more than 12 in.	Boulders and cobbles are very stable components, used for fills, ballast, and to stabilize slopes (riprap). Because of size and weight, their occurrence in natural deposits tends to improve the stability of foundations. Angularity of particles increases stability.
	Cobble	None	Rounded to angular, bulky, hard, rock particle, average diameter smaller than 12 in. but larger than 6 in.	
	Gravel	G	Rounded to angular bulky, hard, rock particle, passing 3-in. sieve (76.2 mm) retained on No. 4 sieve (4.76 mm)	Gravel and sand have essentially same engineering properties differing mainly in degree. The No. 4 sieve is arbitrary division, and does not correspond to significant change in properties. They are easy to compact, little affected by moisture, not subject to frost action. Gravels are generally more perviously stable, resistant to erosion and piping than are sands. The well-graded sands and gravels are generally less pervious and more stable than those which are poorly graded (uniform gradation). Irregularity of particles increases the stability slightly. Finer, uniform sand approaches the characteristics of silt: i.e., decrease in permeability and reduction in stability with increase in moisture.
	Coarse		3 to 3/4-in.	
	Fine		3/4-in. to No. 4	
	Sand	S	Rounded to angular, bulky, hard, rock particle, passing No. 4 sieve (4.76 mm) retained on No. 200 sieve (0.74 mm)	
	Coarse		No. 4 to 10 sieves	
	Medium		No. 10 to 40 sieves	
	Fine		No. 40 to 200 sieves	
Fine-grained Components	Silt	M	Particles smaller than No. 200 sieve (0.74 mm) identified by behavior: that is, slightly or non-plastic regardless of moisture and exhibits little or no strength when air dried	Silt is inherently unstable, particularly when moisture is increased, with a tendency to become quick when saturated. It is relatively impervious, difficult to compact, highly susceptible to frost heave, easily erodible and subject to piping and boiling. Bulky grains reduce compressibility; flaky grains, i.e., mica, diatoms, increase compressibility, produce an "elastic" silt.
	Clay	C	Particles smaller than No. 200 sieve (0.74 mm) identified by behavior; that is, it can be made to exhibit plastic properties within a certain range of moisture and exhibits considerable strength when air dried	The distinguishing characteristic of clay is cohesion or cohesive strength, which increases with decrease in moisture. The permeability of clay is very low, it is difficult to compact when wet and impossible to drain by ordinary means, when compacted is resistant to erosion and piping, is not susceptible to frost heave, is subject to expansion and shrinkage with changes in moisture. The properties are influenced not only by the size and shape (flat, plate-like particles) but also by their mineral composition; i.e., the type of clay-mineral, and chemical environment or base exchange capacity. In general, the montmorillonite clay mineral has greatest, illite and kaolinite the least, adverse effect on the properties.
	Organic matter	O	Organic matter in various sizes and stages of decomposition	Organic matter present even in moderate amounts increases the compressibility and reduces the stability of the fine-grained components. It may decay causing voids or by chemical alteration change the properties of a soil, hence organic soils are not desirable for engineering uses.

TABLE 5-3. ENGINEERING USE CHART [4-10]

Typical Names of Soil Groups	Group Symbols	Important Properties			
		Permeability when Compacted	Shearing Strength when Compacted and Saturated	Compressibility when Compacted and Saturated	Workability as a Construction Material
Well-graded gravels, gravel-sand mixtures, little or no fines	GW	pervious	excellent	negligible	excellent
Poorly graded gravels, gravel-sand mixtures, little or no fines	GP	very pervious	good	negligible	good
Silty gravels, poorly graded gravel-sand-silt mixtures	GM	semipervious to impervious	good	negligible	good
Clayey gravels, poorly graded gravel-sand-clay mixtures	GC	impervious	good to fair	very low	good
Well-graded sands, gravelly sands, little or no fines	SW	pervious	excellent	negligible	excellent
Poorly graded sands, gravelly sands, little or no fines	SP	pervious	good	very low	fair
Silty sands, poorly graded sand-silt mixtures	SM	semipervious to impervious	good	low	fair
Clayey sands, poorly graded sand-clay mixtures	SC	impervious	good to fair	low	good
Inorganic silts and very fine sands, rock flour, silty or clayey fine sands with slight plasticity	ML	semipervious to impervious	fair	medium	fair
Inorganic clays of low to medium plasticity, gravelly clays, sandy clays, silty clays, lean clays	CL	impervious	fair	medium	good to fair
Organic silts and organic silt-clays of low plasticity	OL	semipervious to impervious	poor	medium	fair
Inorganic silts, micaceous or diatomaceous fine sandy or silty soils, elastic silts	MH	semipervious to impervious	fair to poor	high	poor
Inorganic clays of high plasticity, fat clays	CH	impervious	poor	high	poor
Organic clays of medium to high plasticity	OH	impervious	poor	high	poor
Peat and other highly organic soils	Pt	---	---	---	---

SOURCE: LAMBE & WHITMAN; p. 37

Relative Desirability for Various Uses

Rolled Earth Dams			Canal Sections		Foundations		Roadways		
							Fills		
Homogeneous Embankment	Core	Shell	Erosion Resistance	Compacted Earth Lining	Seepage Important	Seepage not Important	Frost Heave not Possible	Frost Heave Possible	Surfacing
---	---	1	1	---	---	1	1	1	3
---	---	2	2	---	---	3	3	3	---
2	4	---	4	4	1	4	4	9	5
1	1	---	3	1	2	6	5	5	1
---	---	3 if gravelly	6	---	---	2	2	2	4
---	---	4 if gravelly	7 if gravelly	---	---	5	6	4	---
4	5	---	8 if gravelly	5 erosion critical	3	7	8	10	6
3	2	---	5	2	4	8	7	6	2
6	6	---	---	6 erosion critical	6	9	10	11	---
5	3	---	9	3	5	10	9	7	7
8	8	---	---	7 erosion critical	7	11	11	12	---
9	9	---	---	---	8	12	12	13	---
7	7	---	10	8 volume change critical	9	13	13	8	---
10	10	---	---	---	10	14	14	14	---
---	---	---	---	---	---	---	---	---	---

TABLE 5-4. SOIL CLASSIFICATION AND ENGINEERING USE CHART [5-1]

MAJOR DIVISION		SOIL GROUP SYMBOLS	SOIL GROUPS & TYPICAL NAMES	GENERAL IDENTIFICATION		OBSERVATIONS AND TESTS RELATING TO MATERIAL IN PLACE	PRINCIPAL CLASSIFICATION TESTS ON DISTURBED SAMPLES	VALUE AS FOUNDATION WHEN NOT SUBJECT TO FROST ACTION
				DRY STRENGTH	OTHER PERTINENT EXAMINATIONS			
Coarse Grained Soils	Gravel & Gravelly Soils	GW	Well-graded gravel and gravel-sand mixtures; little or no fines.	None	Gradation, Grain shape.	Dry unit weight or void ratio; degree of compaction; cementation; durability of grains; stratification and drainage characteristics; groundwater conditions; traffic tests; large-scale load tests; or California bearing tests.	Sieve analysis	Excellent
		GC	Well-graded gravel-sand-clay mixtures; excellent binder	Medium to High	Gradation, grain shape binder examination, wet & dry.		Sieve analysis, liquid and plastic limits on binder	Excellent
		GP	Poorly graded gravel & gravel-sand mixtures; little or no fines.	None	Gradation, grain shape.		Sieve analysis	Good to Excellent
		GF	Gravel with fines, very silty gravel, clayey gravel,poorly graded gravel-sand-clay mixture	Very slight to high	Gradation, grain shape, binder examination, wet & dry.		Sieve analysis, liquid and plastic limits on binder if applicable	Good to Excellent
	Sands & Sandy Soils	SW	Well-graded sands & gravelly sands; little or no fines.	None	Gradation, grain shape.		Sieve analysis	Excellent to Good
		SC	Well-graded sand-clay mixtures; excellent binder.	Medium to high	Gradation, grain shape, binder examination, wet & dry.		Sieve analysis, liquid and plastic limits on binder if applicable	Excellent to Good
		SP	Poorly graded sands; little or no fines.	None	Gradation, grain shape.		Sieve analysis	Fair to Good
		SF	Sand with fines, very silty sands, clayey sands, poorly graded sand-clay mixtures.	Very slight to high	Gradation, grain shape, binder examination, wet & dry.		Sieve analysis, liquid and plastic limits on binder if applicable	Fair to Good
Fine-Grained Soils (containing little or no coarse grained material)	Fine-grained soils having low to medium compressibility	ML	Silts (inorganic) and very fine sands, Mo, rock flour, silty or clayey fine sands with slight plasticity.	Very slight to medium	Examination wet (shaking test and plasticity).	Dry unit weight, water content, and void ratio. Consistency undisturbed and remoulded. Stratification. Root holes. Fissures, etc. Drainage and groundwater condition. Traffic tests, large-scale load tests, California bearing tests, or compression tests.	Sieve analysis, liquid and plastic limits, if applicable	Fair to Poor
		CL	Clays (inorganic) of low to medium plasticity, sandy clays, silty clays, lean clays.	Medium to high	Examination in plastic range.		Liquid and plastic limits	Fair to Poor
		OL	Organic silts and organic silt-clays of low plasticity.	Slight to medium	Examination in plastic range, odor.		Liquid and plastic limits from natural condition and after oven-drying	Poor
	Fine-grained soils having high compressibility	MH	Micaceous or diatomaceous fine sandy and silty soils; elastic silts.	Very slight to medium	Examination wet (shaking test and plasticity).		Sieve analysis, liquid and plastic limits if applicable	Poor
		CH	Clays (inorganic) of high plasticity; fat clays.	High	Examination in plastic range.		Liquid and plastic limits	Poor to very poor
		OH	Organic clays of medium to high plasticity.	High	Examination in plastic range, odor.		Liquid and plastic limits from natural condition and after oven-drying	Very poor
Fibrous organic soils with very high compressibility.		Pt	Peat and other highly organic swamp soils.	Readily identified		Consistency, natural water	texture and content	Extremely poor

LEGEND FOR SOIL GROUP SYMBOLS

C - Clay, plastic-inorganic soil.
F - Fines, material < 0.1 mm.
G - Gravel, gravelly soil.
H - High compressibility
L - Relatively low to medium compressibility.
M - Mo, very fine sand, silt, rock flour.
O - Organic silt, silt clay or clay.
P - Poorly graded.
Pt - Peat, highly organic fibrous soil.
S - Sand, sandy soil.
W - Well graded.

SOURCE: SEELYE; p. 9-12, 9-13

VALUE AS *+ WEARING SURFACE WITHOUT DUST PALLIATIVE	 WITH BITUMINOUS SURF. TREAT.	POTENTIAL FROST ACTION+	SHRINKAGE EXPANSION ELASTICITY	DRAINAGE CHARACTERISTICS	COMPACTION CHARACTERISTICS & EQUIPMENT	SOLIDS AT OPTIMUM COMPACTION u, lb./cu. ft.** e, Void Ratio	CALIFORNIA BEARING RATIO FOR COMPACTED AND SOAKED SPECIMEN	COMPARABLE GROUP IN PUBLIC ROADS CLASS. (P.R.A.)
Fair to Poor	Excellent	None to very slight	Almost none	Excellent	Excellent, Tractor	$u > 125$ $e < 0.35$	>50	A-3
Excellent	Excellent	Medium	Very slight	Practically impervious	Excellent, Tamping Roller	$u > 130$ $e < 0.30$	>40	A-1
Poor	Poor to Fair	None to very slight	Almost none	Excellent	Good, Tractor	$u > 115$ $e < 0.45$	25-60	A-3
Poor to Good	Fair to Good	Slight to medium	Almost none to slight	Fair to practically impervious	Good Close Control Essential, Rubber Tired Roller, Tractor	$u > 120$ $e < 0.40$	>20	A-2
Poor	Good	None to very slight	Almost none	Excellent	Excellent, Tractor	$u > 120$ $e < 0.40$	20-60	A-3
Excellent	Excellent	Medium	Very slight	Practically impervious	Excellent, Tamping Roller	$u > 125$ $e < 0.35$	20-60	A-1
Poor	Poor	None to very slight	Almost none	Excellent	Good, Tractor	$u > 100$ $e < 0.70$	10-30	A-3
Poor to Good	Poor to Good	Slight to high	Almost none to medium	Fair to practically impervious	Good, Close Control Essential, Rubber-Tired Roller	$u > 105$ $e < 0.60$	8-30	A-2
Poor		Medium to very high	Slight to medium	Fair to poor	Good to Poor, Close Control Essential, Rubber-Tired Roller	$u > 100$ $e < 0.70$	6-25	A-4
Poor		Medium to high	Medium	Practically impervious	Fair to Good Tamping Roller	$u > 100$ $e < 0.70$	4-15	A-4 A-6 A-7
Very Poor		Medium to high	Medium to high	Poor	Fair to Poor Tamping Roller	$u > 90$ $e < 0.90$	3-8	A-4 A-7
Very Poor		Medium to very high	High	Fair to poor	Poor to Very Poor	$u > 100$ $e < 0.70$	< 7	A-5
Very Poor		Medium	High	Practically impervious	Fair to Poor, Tamping Roller	$u > 90$ $e < 0.90$	< 6	A-6 A-7
Useless		Medium	High	Practically impervious	Poor to Very Poor	$u > 100$ $e < 0.70$	< 4	A-7 A-8
Useless		Slight	Very high	Fair to poor	Compaction not Practical Replace with Compactible Material			A-8

NOTES:

* Values are for subgrade and base courses, except for base courses directly under wearing surface.

+ Values are for guidance only. Design should be based on test results.

** Unit weights apply only to soils with specific gravities ranging between 2.65 and 2.75.

5.2.1 Strength, Compressibility, and Permeability Factors

The strength, compressibility, and permeability of soil affect their use in civil engineering projects. Cohesionless soils such as sands and gravels (GW and SW, Table 5-3) display relatively high shear strength, high permeability and low compressibility when compared to clays (CL). The relatively high strength of sands and gravels makes them suitable to support buildings with a minimum of settlement under the load of the structure. Their high permeability provides good drainage, both during and after construction. These soils are easy to place and compact when used as backfill.

Clay soils, on the other hand, are weaker and more compressible under building loads and have poor drainage characteristics. The low permeability, however, can be useful when levees or dikes are required to hold out flood waters.

Typical values of strength, compressibility, and permeability for rock, sand and gravel, and clay muck are presented in Table 5-5. A range of values for each parameter is provided for comparison purposes. Laboratory tests should be conducted in order to confirm the soil properties for use in a specific project.

TABLE 5-5. TYPICAL SOIL PROPERTIES FOR MUCK

Parameter	Muck Category		
	Rock	Sand and Gravel	Clay (Remolded)
Strength:			
1. Unconfined Compressive Strength; q_u, psi	Not Appropriate	Not Appropriate	3.5 to 140 (0.25 to > 10 tsf)
2. Angle of Internal Friction ϕ, degrees	40 to 50 (1)	30 to 45 (1)	22 to 32
and			
Cohesion Intercept, c, tsf	0 (1)	0 (1)	0 to > 14.0 (0 to > 1.0 tsf)
Modulus of Elasticity, E, psi	(2)	(2)	(100 to 400) x q_u
Compressibility:			
1. Compression Index, C_c, for			
Vertical Stress: 10-100 psi	0.01 to 0.03	0.01 to 0.03	0.1 to 0.8
> 200 psi	0.4 ± 0.1	0.4 ± 0.1	—
Permeability:			
1. Coefficient of Permeability K, cm/sec	10^{-3} to 10^{2}	10^{-3} to 10^{2}	10^{-9} to 10^{-6}

Notes: (1) For continuing stresses below 100 psi.

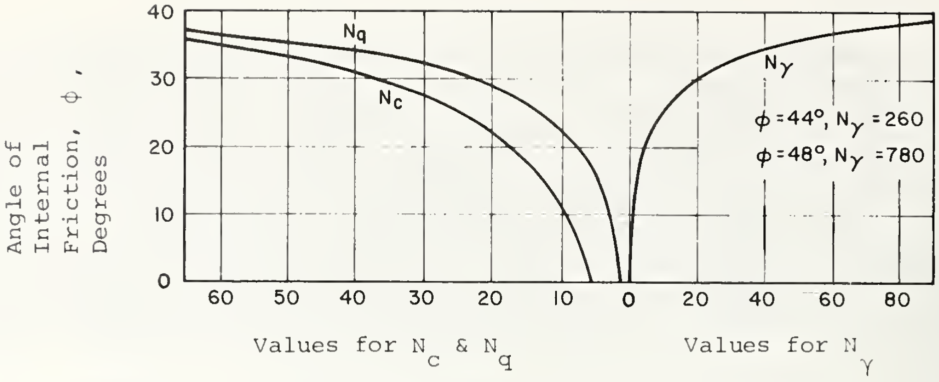
(2) Refer to soil properties, Section 4.

The basic soil properties are used in engineering analyses to determine the allowable bearing capacity for spread footings and the vertical settlement under loads, and to analyze slope stability and drainage problems. In general, cohesionless soils with high values for the angle of internal friction, develop high values of bearing capacity, do not settle significantly under load, and remain stable on steep slopes. For example, the ultimate bearing capacity for a 5 x 5 ft spread footing, founded 4 ft deep, in compacted fills of rock, sand and clay muck are listed below. These values were calculated in accordance with the classical method of bearing capacity analysis shown in Figure 5-1.

	Rock	Sand	Clay
Ultimate Bearing Capacity (tsf)	>20	6.2	4.7
Assumed Strength Parameters			
ϕ, degrees	40	30	22
C, tsf	0	0	0.1

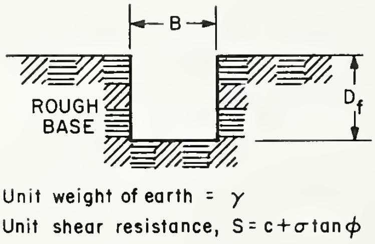
The design of a spread footing foundation must account for bearing capacity and settlement. This simple calculation illustrates that both rock muck and sand muck are more desirable than clay since rock and sand muck have higher bearing capacities. A discussion of settlement analysis methods is beyond the scope of this report. However, a settlement analysis would indicate that rock or sand muck is still preferred over clay muck because (1) under the same loading, sand and rock settle less than clay and (2) sand and rock settle more rapidly under the same load than clay.

The engineering properties of tunnel muck can be used to determine the potential for utilization of the material in a civil engineering project. The parameters can either be evaluated from laboratory tests on representative samples or, in some cases, determined from field tests. A common field test is the plate bearing test, which is used to confirm in-situ bearing capacity. It is preferred that field tests be conducted on a test section which simulates the design condition. It is unlikely, however, that a test section could be prepared prior to the start of production tunneling, due primarily to the scope of work involved. Preliminary decisions can be made to indicate the general suitability of the material. In this latter case, the laboratory testing program would provide the data for the decision making process. Therefore, prediction of engineering properties of muck will depend principally on laboratory testing of small volumes of material.



Bearing Capacity Factors versus Angle of Internal Friction

where



and the ultimate bearing capacity, q, per unit area is given by:

continuous footing: $q = cN_c + \gamma \frac{B}{2} N_\gamma + \gamma D_f N_q$

square footing: $q = 1.3\ cN_c + 0.4\ \gamma N_\gamma + \gamma D_f N_q$

circular footing: $q = 1.3\ cN_c + 0.3\gamma\ N_\gamma + \gamma D_f N_q$

FIGURE 5-1. BEARING CAPACITY FACTORS FOR SHALLOW FOUNDATIONS [4-2]

SOURCE: TERZAGHI & PECK; p. 222

5.2.2 Engineered, Compacted Fill

Soil and rock materials used to support structures or construct significant earthwork structures, such as earth dams, must be placed in a manner which assures the quality of the end product. The term "engineered, compacted fill" designates that the placement of materials conforms to engineering design, control, and construction methods. Tunnel muck with appropriate engineering characteristics can be used in engineered, compacted fill (or structural landfills).

Structural landfills are costly because only select materials can be used and because the material must be placed in thin layers and thoroughly compacted. In general, a structural landfill would only be constructed at a site for which specific development plans have been formulated and only if the developer is paying for delivery of the fill and placement costs. In this case, the compressibility of the fill would be reduced and the strength increased as much as practicable in a short time so that the proposed construction could begin immediately.

A recent survey of engineering practice in the New England area indicates that engineered, compacted fill has performed satisfactorily [5-2]. After constructing a compacted fill, either to raise the grade or to replace unsuitable materials, the building foundation can be constructed at nominal depths.

The construction of an engineered, compacted fill requires proper design and construction procedures. Specifications for engineered, compacted fill projects generally establish the requirements for: (1) acceptable materials, (2) method of placement, and (3) percent compaction or density criteria. Certain types of muck satisfy the criteria presented in the following paragraphs.

5.2.2.1 Material Specifications

Materials used in engineered, compacted fill must satisfy gradation and general descriptive requirements. To meet the descriptive requirements, borrow material must generally consist of sound, hard, durable mineral aggregate free of ice, snow, frozen or organic soil, elastic or deleterious foreign matter (such as metallic debris), and that it must be properly graded to permit satisfactory compaction. These requirements are supported by gradation or engineering property specifications depending on the regional nature of the soils.

For example, gradation specifications appropriate to the New England area are illustrated in Figure 5-2. The materials normally consist of bank-run sandy gravel or gravelly sand obtained from gravel pits or borrow areas. Note that the specifications require that less than 10 percent of the borrow consist of silt or clay. Compressible clayey or silty soils, which are also susceptible to frost penetration problems, are not acceptable.

The soil conditions in Georgia, on the other hand, are different from those in New England, and engineering practice reflects the difference. Residual soils composed of angular sands and friable sand clays are available and therefore are utlized in compacted fill projects. Volume change criteria resulting from clays must be considered. Table 5-6 indicates the soil classifications and properties used in highway construction in Georgia.

An inspection of the gradation curves for rock, sand and clay muck indicates the following trends:

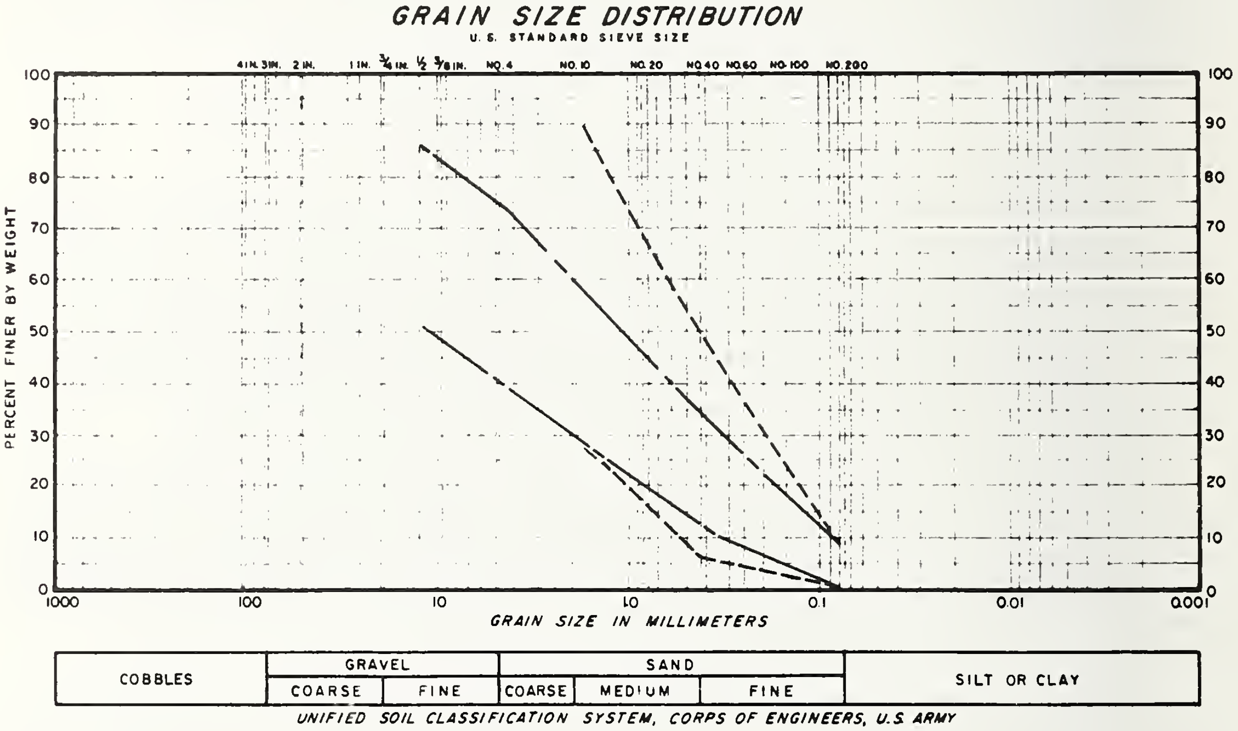
a. Drill and blast rock muck is too coarse. The voids between large rock blocks could result in unacceptable settlement.

b. TBM rock muck generally meets the gradation specifications.

c. Sand and gravel muck also meets gradation requirements, certain fine sand mucks are acceptable.

The acceptability of muck for use in a particular project depends on the local material specifications and the results of laboratory tests conducted to determine engineering properties of the muck. The results of a thorough engineering analysis, however, may even prove that, in special cases, rock muck could be utilized in engineered, compacted fill. Two and three story buildings in Binghamton, New York were satisfactorily supported on rock fill [5-2].

Raw muck could also be processed in order to satisfy the gradation specifications. Methods of sorting, screening, washing and crushing are described in Section 5-4.



Symbol	Source
———-———	Massachusetts Highway Specification, Section M1.03.0 [5-3]
- - - - - - - -	Haley & Aldrich, Inc., File No. 3555 [5-4]

FIGURE 5-2. GRADATION SPECIFICATIONS FOR ENGINEERED, COMPACTED FILL IN NEW ENGLAND

TABLE 5-6. GEORGIA HIGHWAY SPECIFICATIONS - PROPERTIES OF ROADWAY FILL MATERIALS [5-5]

SECTION 810.

ROADWAY MATERIALS

810.01. Roadway Materials: Materials for roadway construction shall not contain any logs, stumps, sod, weeds, or other perishable matter. They are divided into six major classes, and Classes I, II and III are further subdivided and are identified by description and physical property requirements as specified in Table 810-1. Classes IV, V and VI are identified by descriptive requirements.

A. CLASSES

Class I. This class consists of well-graded, angular sands, and friable sand clays.

Class II. This class consists of well to poorly graded sands and clay soils with low volume change properties.

Class III. This class consists of low density, poorly graded sands; clay soils with high plasticity and volume change properties; disintegrated rock which is easily broken down during manipulation; and low-density, inorganic soils.

Class IV. This class consists of highly organic soils or peat, muck and other unsatisfactory soils generally found in marshy or swampy areas.

Class V. This class consists of shaly materials which are not only finely laminated but have detrimental weathering properties and tend to disintegrate.

Class VI. This class consists of rock or boulders which cannot be readily incorporated into the embankment by layer construction, and which contain insufficient material to fill the interstices when they are placed.

B. TESTS: Methods of tests shall be in accordance with the following:

Soil Gradation	GHD: 4
Volume Change	GHD: 6
Maximum Density	GHD: 7

TABLE 810-1

PHYSICAL PROPERTIES OF MATERIAL PASSING

NO. 10 SIEVE

Class	No. 60 Sieve % Passing	No. 200 Sieve % Passing	Clay %	Volume Change %	Maximum Dry Density lb/ft 3
I-A	15-85	0-35	0-16	0-10*	100+
I-B	15-85	16-45	16-30	0-12*	110+
II-A		0-45	0-16	0-10*	95+
II-B		0-55	16+	0-15*	100+
III-A		0-75		0-25	90+
III-B				0-50	80+
III-C				0+	80+

*Note: Class I or II soils having total volume change exceeding 8.0% with swell greater than 2/3 of the total volume change will be classified as III-A.

5.2.2.2 Method of Placement

In order to obtain satisfactory long-term performance, the fill materials must be placed in horizontal layers, typically 8 to 12 in. thick, and rolled or compacted by construction equipment. Methods of compaction are described in subsequent sections of this report.

During the placement operation, oversized materials or debris can be removed from the fill. "Rock rakes" fitted to bulldozers are often used. Standard construction equipment can be used to compact tunnel muck.

5.2.2.3 Compaction or Density Requirements

In order to produce adequate strength and minimize settlement, the fill must be compacted to a specified density which varies for each soil material. Two criteria are used to obtain satisfactory density: (1) a minimum number of passes of specified compaction equipment and/ or (2) a minimum density expressed as a percentage of a laboratory maximum dry unit weight. The number of passes of equipment is usually established from a trial or test section where soil densities are measured. Control of field work by this procedure is applicable if the fill material does not vary significantly in gradation or compaction characteristics.

The combination of a minimum number of coverages and a density requirement enables better control over the construction process. This procedure is better suited to muck utilization since the advancing tunnel excavation penetrates varying soil and rock deposits. Usually the fill must be compacted to a minimum density of about 95 percent of the laboratory maximum dry unit weight. A discussion of the test procedure is presented in other sections of this report.

5.2.3 Controlled Fill

Controlled fill is loosely defined as soil and rock materials placed to construct a stable embankment or soil structure conforming to design requirements. The controls on material quality and compaction for controlled fill are not as restrictive as the requirements for engineered, compacted fill for support of structures. Examples of uses for controlled fill are construction of highway and railway embankments, backfill around structures and in trenches, parking lots, and restoration of gravel pits and quarries.

The applicability of controlled fill can be determined, in part, by assessing the consequences of excessive settlement, swelling or other "failure" of the earthwork structure. For example, failure of an earth dam would be a major catastrophe and therefore the dam must be built as an engineered-compacted fill. Settlement of a highway embankment, on the other hand, could produce a crack or bump in the pavement which would be uncomfortable but not catastrophic. However, continual maintenance of a highway pavement can be an expensive process and therefore a certain degree of control is necessary during construction of the embankment.

Controlled fills usually provide satisfactory support for minor structures, parking lots, utilities and roadways. For structures, differential settlements are greatly reduced and damage will be minimal even if the total settlement is still quite large. Parking lots built on controlled fill are firm and stable and relatively free of potholes and puddles. Utilities remain intact and do not break in the ground or at the point of connection with structures. Controlled fills for roadway embankments have been used for years as designers try to balance cuts and fills using the material available along the line of the highway. Most state department of public works have developed specifications relative to acceptable construction procedures for controlled fills.

5.2.3.1 Materials

Acceptable soil and rock materials for controlled fills can be characterized as natural, inorganic, soil or rock free of deleterious substances such as logs, stumps, frozen soil, ice and other unacceptable materials.

Highway embankments are usually constructed from materials obtained from "cut" sections of the roadway alignment. Thus blast rock and various soil deposits are utlized, reducing or eliminating the need to import expensive borrow materials. Of the available materials, the poorest quality materials are placed in the deepest portions of the fill, and the best materials are used at the top of the embankment.

All classes of tunnel muck (i.e., rock, sand, and clay) are suitable for most controlled fill projects. Naturally, the better quality materials are suitable for more projects. Since materials such as blast furnace slag may be satisfactory for controlled fill [5-6], tunnel muck must also be considered as a realistic source for controlled fill materials.

The screening or sorting of debris from the fill is required, but not to the same extent as for an engineered, compacted fill. Items such as large timbers and trash must be removed, but broken concrete and steel reinforcing bars are not detrimental to the overall performance of the fill. (Refer to subsequent sections for a discussion of muck processing.)

5.2.3.2 Method of Placement

Specifications generally require that materials used in controlled fills be placed in horizontal layers and rolled or compacted by construction equipment. The thickness of the layer is dependent upon material gradation and intended use. For example, blast rock used in highway embankments may be placed in layers several feet thick and compacted by heavy duty equipment. Backfill next to a building or pipeline usually requires 6 in. thick layers and compaction by lightweight, hand operated, equipment. Maximum particle size may be restricted to less than 3 in. in these close compaction quarters. TBM muck would satisfy the maximum particle size for the latter case.

5.2.3.3 Compaction and Density Requirements

Vertical or lateral movements of controlled fills are not critical since major catastrophes are not involved. Compaction requirements are therefore less stringent than those required for engineered, compacted fill. Where a structural fill requires minimum field densities of about 95 percent of the laboratory maximum density, a controlled fill generally requires only 90 to 92 percent.

Backfilling of quarries or sand and gravel pits is not critical. Therefore, compaction requirements may be stated as only a few passings of a bulldozer or equivalent equipment. Layer thickness may also be increased to several feet.

If the landfill area will eventually be used to support structures, it is economical to place the fill with sufficient compactive effort to eliminate future settlement problems. There are methods available, however, which can be utilized to improve the engineering properties of soil deposits for all types of project sizes. A complete discussion of these methods, including soil stabilization, vibroflotation, and grouting, is contained in Section 5.5 of this report.

5.2.4 Uncontrolled Fill

General landscaping, site grading activities, backfilling of basements from demolished structures, and construction of surcharges fall into the category of uncontrolled fill. No significant controls are placed on the filling operations with respect to either types of material or their method of placement. The sign advertising "Solid Fill Wanted" typifies this category of earthwork construction. Most tunnel muck, including tunneling debris and possibly rubble from demolition work, ends up in an uncontrolled or miscellaneous fill.

Clay-based miscellaneous landfill is usually highly compressible and has very low strength. Sand and gravel-based miscellaneous landfill has highly variable properties: dense, strong areas beneath haul roads, and loose, weak zones elsewhere. The loose areas are compressible and possibly subject to liquefaction. Rock-based miscellaneous landfill can be composed of very large particles enclosing voids which result in localized sink holes as cover materials wash down into the voids.

Although miscellaneous uncontrolled landfills are convenient for the hauling contractor and may save money for the project under construction, it is difficult to plan for their future utilization. The engineering properties and the problems associated with future construction on a miscellaneous landfill cannot be evaluated in any practical way. The strength, compressibility, and permeability of the deposit cannot be predicted.

For developers who measure the total cost of a site as the cost of the land plus the cost of foundation construction, a miscellaneous uncontrolled landfill can result in significant cost increases even if the site needs to be filled and the miscellaneous fill is delivered free of charge.

Despite these difficulties, miscellaneous landfills may be suitable for parks and parking lots. Even though sidewalks and pavements crack, and sink holes and large puddles develop, immediate availability of the fill may overshadow these disadvantages.

5.2.5 Surcharging

A surcharge is a temporary fill constructed above the proposed site elevation in order to precompress and strengthen the underlying soils. Ideally, this method improves the soil sufficiently so that deep foundation support becomes unnecessary. At the very least, it greatly improves the performance of shallow foundations, paved areas, and utility corridors. This improvement of subsoil performance makes the site more valuable by decreasing foundation and future maintenance costs. This increase in value is usually enough to offset the cost of handling the surcharge [5-7].

Almost any soil material can be used in a surcharge although stable, inorganic soils are preferred. Organic, clayey and highly compressible soils are difficult to handle and can lead to stability problems while the surcharge is in place. These soils can be used for surcharging, however, if they are readily available and allowance for reasonable contingencies relative to their use does not increase the cost beyond that for more satisfactory surcharge materials.

Forming a surcharge is not a true utilization of tunnel muck since the surcharge itself will eventually have to be removed if the site is to be utilized. Surcharging does, however, provide excellent temporary storage for muck until it can be used more profitably elsewhere. In particular, the muck might be reused as backfill on portions of the transportation system where the muck was produced in the first place. This sequence of events is an excellent example of low-cost muck utilization with limited impact on the environment.

5.2.6 Sanitary Landfill

Sanitary landfills are used by many urban areas for waste disposal. Although a complete discussion of sanitary landfill technology is beyond the scope of this report, a brief description will serve to demonstrate how muck can be utilized in such an operation. Figure 5-3 shows a typical landfill operation where the trash delivered each day is covered by inorganic soil to form a cell. Cell construction continues each day until a lift is formed from the cells and until the entire site is filled with lifts. At that time, the final cover layer is placed, graded and seeded.

The advantages of treating solid wastes in this manner are numerous. Foremost is the elimination of air pollution from open burning and decomposition. The disadvantages associated with sanitary landfills are the inability to obtain suitable large disposal sites in the vicinity of urban areas and the lack of good cover material. Unfortunately, as an urban area becomes larger, the amount of solid wastes increases and the amount of available land decreases. These two factors combine to make the operation of a sanitary landfill relatively expensive for most large urban areas.

Tunnel muck can be used to overcome the problem of obtaining cover material. Although almost any inorganic soil can be used for cover material, some soils are more suitable than others. Clayey soils provide good moisture barriers but have poor trafficability. Sandy soils provide good trafficability and allow gases to escape, but are not as good for fire control. In general, well-graded sandy soils with fines are the best cover materials. Clayey soils can be used at specific locations for moisture and gas control. Boulders should be avoided because they are difficult to compact. Table 5-7 summarizes the suitability of different kinds of cover material.

The volume requirements for cover material in a sanitary landfill can be estimated using simple formulas. In general, cover material is used in the ratio of approximately one cu yd of fill to three or four cu yd of waste material. For a typical sanitary landfill handling 1500 cu yd of trash per day, approximately 400 to 500 cu yd of cover material per day are needed.

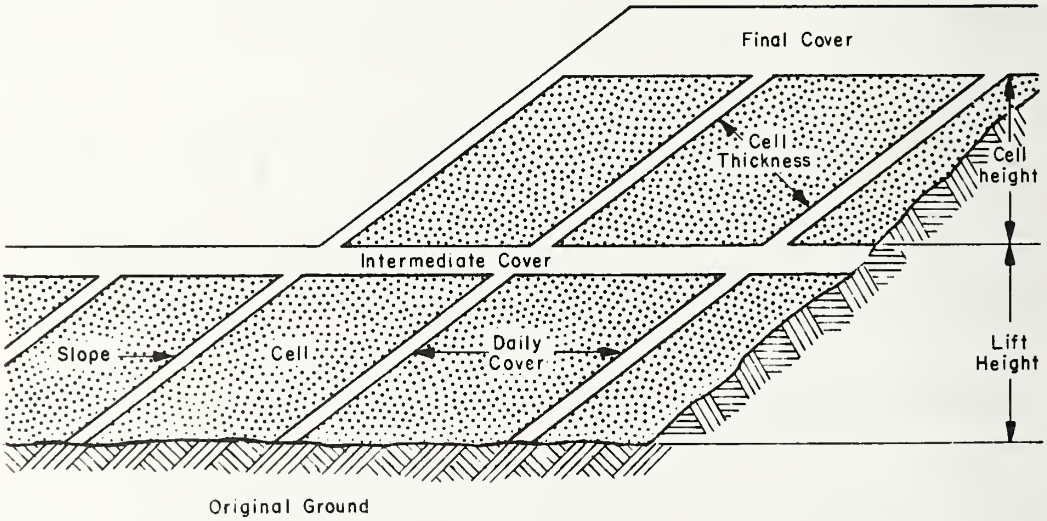


FIGURE 5-3. TYPICAL SANITARY LANDFILL CELL

TABLE 5-7. REQUIREMENTS FOR SANITARY LANDFILL COVER MATERIALS [5-8]

SOURCE: BRUNNER & KELLER; p. 14

Function	Clean gravel	Clayey-silty gravel	Clean sand	Clayey-silty sand	Silt	Clay
Prevent rodents from burrowing or tunneling	G	F-G	G	P	P	P
Keep flies from emerging	P	F	P	G	G	E[†]
Minimize moisture entering fill	P	F-G	P	G-E	G-E	E[†]
Minimize landfill gas venting through cover	P	F-G	P	G-E	G-E	E[†]
Provide pleasing appearance and control blowing paper	E	E	E	E	E	E
Grow vegetation	P	G	P-F	E	G-E	F-G
Be permeable for venting decomposition gas[§]	E	P	G	P	P	P

[*] E, excellent; G, good; F, fair; P, poor.

[†] Except when cracks extend through the entire cover.

[§] Only if well drained.

5.3 SPECIALIZED USES OF TUNNEL MUCK

Many specialized uses of tunnel muck are possible with only moderate processing. For clay-based muck, the possibilities include fired clay products such as brick, clay pipe, and lightweight aggregate, and as a raw material in the manufacture of portland cement. Sand and gravel-based muck can be used in highway and airfield subbases, concrete, and bituminous pavement. Crushed stone can be used for all of the sand and gravel uses, as well as macadam and railroad ballast for which an angular material is preferable. Blast rock can be used for river riprap and shore protection. The production of loam is also possible from certain types of tunnel muck.

A summary of the major problems associated with specialized utilization of tunnel muck is given below, so that specialized uses can be considered in a realistic framework:

a. Tunnel and trucking contractors, the traditional muck handlers, do not have the expertise or capital to establish a specialized processing plant for refinement of muck. Outright disposal is often easier and cheaper for them.

b. Construction schedules do not allow time for complicated processing. Valuable material is stockpiled, and stockpiling becomes the method of disposal for the tunnel contractor.

c. An expensive processing operation must be capitalized for extended periods of time and needs a continuous and long-term supply of raw materials. Tunnel muck is usually not supplied continuously, and the duration of supply is certainly limited.

d. Raw material cost is very often less important than raw material quality in complicated manufacturing processes, and quality of tunnel muck cannot be assured.

e. Processors find that the debris in muck is an expensive nuisance.

5.3.1 Fired Clay Products

Because of its low cost, ease of handling and molding, and ability to harden when heated, clay has been used for centuries to make bricks, tiles, pipes, and cooking and eating utensils. In many countries, clay products are still produced by simple hand methods as they have been for centuries. More developed countries use modern, high-capacity processing equipment. Clay muck is a potential source of raw clay material.

Briefly, the manufacturing process involves mixing clay with other soils and chemicals to form a uniform, plastic mass and molding it into desired shapes. After molding, the clay is dried and then heated in a carefully controlled sequence in large kilns for periods of up to one week and at temperatures as high as 2200°F. This process, called firing, causes the clay to fuse and harden into a solid material.

Fusing of the clay actually takes place in three different stages of temperatures, the ranges of which change somewhat depending on the type of clay. The first stage occurs in a temperature of approximately 1800°F and is called incipient fusion. During incipient fusion the clay is completely dehydrated and oxidized to become a strong, hard mass with low absorbency. Many fired clay products, such as bricks, are not fused beyond this stage. If the temperature is increased to a range of 1800 to 2200°F, vitrification takes place. Vitrification results when the bond between clay particles breaks down and new, stronger bonds within the mass are formed. Clay pipe and ceramic tile are typical vitrified clay products. As the temperature is increased above 2200°F the clay enters the stage called viscous fusion which is characterized by melting of the clay. Viscous fusion is not part of fired clay processing because it represents a destructive stage of clay fusion in which the molten clay will not hold a shape and becomes very brittle upon cooling.

Although most clays harden when heated, it is difficult to select a clay that will withstand processing and produce a high quality finished product. Successful processing requires good workability, low shrinkage, and the absence of impurities harmful to the dryers and kilns. High quality finished products have high strength and predictable shade and color.

The most fundamental properties of clay relative to fired clay processing are plasticity, shrinkage, tensile strength and fusibility. Each of these must be carefully analyzed to determine if a clay is suitable for production. Most clays are not entirely satisfactory, and production trade-offs are necessary to obtain the most economical procedures. Highly plastic clays, for example, improve workability but also result in the largest amount of shrinkage upon drying.

Plasticity is defined as the ability of a material to deform under the application of pressure and to retain the deformed shape when the pressure is removed. For engineering purposes, all clays exhibit plasticity by definition. A highly plastic clay will remain plastic throughout a broad range of water contents and will impart plasticity to other soil types even if the clay makes up only 20 to 25 percent of the total weight of the mixture. Low plasticity clays are avoided for fired clay production because they either liquefy or crumble within a small range of water content and greatly restrict workability. Clays with extremely high plasticity, like montmorillonite, are also avoided in fired clay production because they require large quantities of water to produce a plastic mass and shrink four to five times as much during drying as other clays. Small amounts of montmorillonite are sometimes used as an additive to improve workability of other clays.

Shrinkage is a very important characteristic of any clay material being used for fired clay products. Both the total amount of shrinkage and the potential for differential shrinkage must be evaluated. Total shrinkage generally ranges between 5 and 15 percent of the original volume of the mold. Compensation is provided by adjusting the size of the molds or machine dies.

Differential shrinkage is caused primarily by nonuniformity in the original mix and by uneven heating during firing. Nonuniformity in the mix results if the clay type or water content varies within a batch. Thorough blending is necessary. Differential shrinkage can also be caused between batches if the natural clay deposit is erratic or if quality control during batching is poor.

Tensile strength and fusibility are interrelated in that the strongest final product must be produced for the least expenditure of time and material. High tensile strength minimizes warping and cracking during processing and breakage during shipment of the finished product.

Another important aspect of the suitability of clay for fired clay production is an analysis of impurities. All clays contain "impurities" such as iron, magnesium, potasium and lime. Many of the metal ions serve as fluxing agents by lowering the fusion point. Iron is particularly important because it greatly influences the final color. If iron is present in amounts greater than four percent of the total weight, the final product will be red. Other impurities, such as alkali, leave deposits inside the dryers and kilns which require repeated equipment cleaning.

As a result of the complexity of the process, manufacturers are most concerned about the quality and reliability of the raw clay ingredients. Tunnel muck can rarely meet these two critical requirements.

5.3.2 Lightweight Aggregates

A variety of methods exist today for the production of lightweight aggregate. Blasting of volcanic deposits produces a natural lightweight aggregate, usually exhibiting very low strengths, which is suitable for use in insulating concrete or concrete for masonry units. The method most applicable for the utilization of tunnel muck involves the expanding, or bloating, of certain clays, shales, or slates. This type of synthetic aggregate can be used in concrete for structural members. Standards have been established for the various types of lightweight aggregate under the following ASTM Designations:

ASTM Designation	Standard Specification for Lightweight Aggregates for:
C330	Structural Concrete [5-9]
C331	Concrete Masonry Units [5-10]
C332	Insulating Concrete [5-11]

The production of lightweight aggregate involves the heating of the raw material (clay, shale, or slate) to incipient fusion, usually from 1800°F to 2200°F, at which point bloating takes place. The bloating action requires the occurrence of two simultaneous conditions. First, the raw material must reach the proper pyroplastic condition to be able to expand without rupture or subsequent collapsing. Second, the raw material must generate gas at the proper time and in the right amount. The resulting cellular structure is then cooled and further processed.

No clear cut relationship seems to exist between the bloating potential of a raw material and its physical or chemical properties. The formation of a pyroplastic condition depends strictly on temperature. The expulsion of gas by the raw material is produced by a reduction of iron oxide and a liberation of sulfur dioxide, carbon monoxide, and carbon dioxide from the chemical elements within the bloating material [5-12].

The most basic and perhaps simplest method to determine the potential utilization of tunnel muck as a bloating material is to perform a test run in a small stationary kiln that closely simulates the heating schedule and kiln atmosphere. Materials which do not bloat may be improved by blending them with a bloating material or by adding relatively cheap materials which contain the needed gas forming or fluxing compounds. These additives contain compounds of iron, sulfur, carbon, alkali and alkaline earths. Fluxes containing sodium or potassium (e.g. feldspar) are excellent compounds which can keep a mass highly viscous at the time of gas expulsion. Carbonaceous materials help expand the range of vitrification by lowering the melting point of the raw material.

Lightweight aggregate properties are largely dependent on the raw materials used and the manufacturing process. The most desirable aggregate properties are listed below [5-13].

a. They should be uniform in composition and properties.

b. They should be suitably graded for their intended use, and the desired grading should be maintained.

c. They should have a low specific weight to provide a worthwhile saving in weight of the structure, and the desired special properties associated with lightweight, such as high thermal insulation.

d. They should have a large number of small, well dispersed internal voids, but should have a minimum number of large external voids that have to be filled with mortar or paste.

e. Individual pieces should have adequate strength and should be firm and hard enough to withstand handling and mixing without breaking down in size.

f. The particles must bond well with the cement paste and must not react chemically with cement or reinforcing steel.

g. They should have good resistance to weathering, moisture, insects, and fungi.

Some typical properties of all types of lightweight aggregate are listed in Table 5-8. An important criterion to be met in the production of lightweight aggregate is uniformity. A prime cause of nonuniformity is differences in sources of the raw material. It may therefore be necessary, in addition to the removal of obvious undesirable material such as metal, rock chunks, and wood pieces, that clay tunnel muck may require a second screening process to further purify the raw material.

In addition, lightweight aggregate should be free of:

a. Materials reactive with alkalies in cement

b. Unhydrated pieces of hard burned lime or magnesia

c. Calcium sulfate or unstable iron compounds

d. Organic impurities

e. Unburned clay particles

f. Other foreign materials which adversely affect desirable properties such as appearance

TABLE 5-8. PROPERTIES OF LIGHTWEIGHT MINERAL AGGREGATES [5-13]

Aggregate	Specific weight, lb. per cu. ft.	Bulk specific gravity	Absorption, percent by weight	Crushing strength at 2 in. compaction psi
Exfoliated vermiculite	0-12	0.9-1.3	20-35	35-45
Expanded perlite	4-16	0.7-1.1	10-50	60-400
Expanded slag	30-70	1.2-2.4	5-25	150-2000
Expanded shale, clay, slate	35-75	1.1-2.2	5-20	2000-16,000
Sintered fly ash	40-60	1.7-2.1	8-15	1000
Purnice	25-60	1.0-1.7	8-50	1000-2000

*Based largely on information provided in "Lightweight Aggregate Concretes" issued in August, 1949 by Housing and Home Finance Agency.

SOURCE: WASHA; p. 379

5.3.3 Portland Cement

Muck from either soft ground or hard ground tunneling operations may be used in the manufacture of portland cement provided the necessary chemical compounds are present in the desired proportioned amounts. The muck or raw material must supply one or more compounds containing lime, silica, or alumina. Common sources for lime are natural calcareous deposits such as limestone, marine shells, marl and chalk. The siliceous or argillaceous compounds can be obtained from deposits of clay, shale, slate, and sand. A few special materials, such as argillaceous limestone, commonly called "cement rock", contain combinations of all three compounds. In some instances where a particular raw material may lack any of the required compounds, supplemental materials of suitable composition may be used to adjust the raw mix.

In addition to lime, silica, and alumina, most of the abovementioned materials contain additional substances such as iron, magnesium, alkalines and phosphates. Iron helps to control the amount of by-product formed during some of the chemical reactions. It also acts to lower the fusion point of some reactions. The grayish color of most portland cements is a direct result of the presence of iron.

The remaining additional substances, if present in large enough quantities, may have deleterious effects on the finished product. On occasion, a special preliminary process may have to be employed in the overall manufacturing process to regulate the presence of some of these substances.

The manufacture of portland cement begins when the raw materials are brought to the plant, subjected to preliminary treatment, such as washing, screening, and crushing, and placed in separate storage bins. After a complete chemical analysis, the raw materials are then proportioned together so that the finished product will consist of the desired chemical composition. Typically, the Type I Portland cement contains 60-66 percent lime, 19-25 percent silica, 3-8 percent alumina, 1-5 percent iron, 0-5 percent magnesia, and 1-3 percent sulfur trioxide.

Grinding and blending of the raw materials can be accomplished either in a dry process or a wet process. In both processes, the raw materials must be finely ground and well mixed to ensure a complete reaction between all compounds during processing.

The next procedure involves burning of the blended raw materials in rotary kilns. The inclination and rotation speed of the kiln control the rate at which the material passes through the kiln. The temperature gradually increases to a range of from 2500 to 2900°F, at which point the mix fuses into small lumps, called clinker, ranging in size from 1/16 to 1 or 2 in. in diameter.

After the clinker is cooled, it is mixed with 4 to 5 percent by weight of a calcium sulfate mineral, usually gypsum, and then ground extremely fine. The gypsum helps to control the setting time of cement as it is mixed with water.

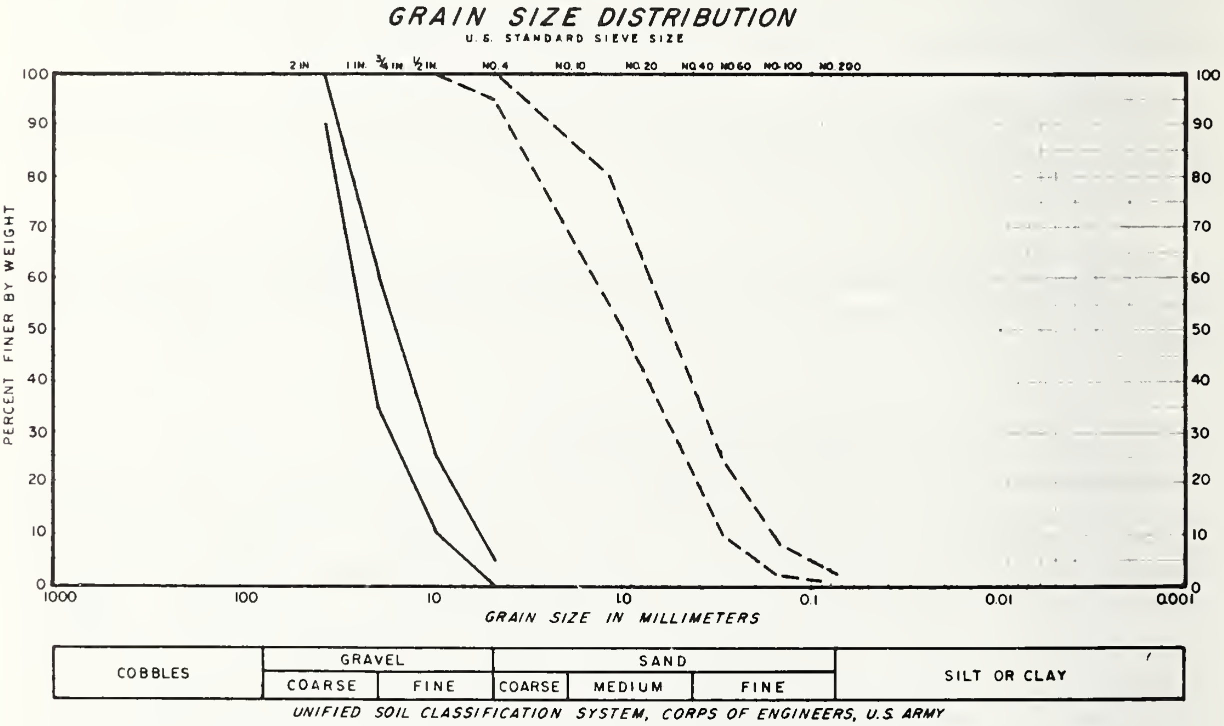
Samples of tunnel muck, or samples obtained during the exploration program would have to be evaluated by a particular manufacturing agency in order to determine the acceptability of the muck as a raw material.

5.3.4 Portland Cement Concrete Aggregates

Aggregates for portland cement concrete are divided into two general categories: (1) coarse aggregate and (2) fine aggregate. Coarse aggregate consists of crushed rock, crushed stone, crushed slag, or other approved material such as lightweight aggregate. Fine aggregate consists of natural sand or manufactured sand-crushed rock. Tunnel muck is a potential source for each type of aggregate. Also, since concrete aggregates are normally processed material, i.e. crushed, screened and washed, the construction debris normally found in muck can be easily removed. If tunneling or excavation for structures will pass through a geologic deposit such as sound rock or sand and gravel, then samples of the materials should be tested to determine their suitability for aggregates.

Acceptability tests conducted on aggregates include: gradation, silt content, presence of organic or other undesirable material, soundness, resistance to abrasion, chemical reaction, and petrographic analysis [5-15]. The general purpose of the tests is to determine that the aggregates consist of clean, hard, strong and impermeable particles, resistant to wear and frost, and free from deleterious amounts of organic matter, loam, clay, salts and weak grains. Also coarse aggregate should not be long and thin, and sand particles should be nearly spherical and should have gritty surfaces. The test procedures established in standard specifications, such as ASTM or AASHO, have been generally adopted. These tests or specification limits may be modified slightly to account for local practice. For example, the Massachusetts highway specifications establish a maximum loss by the Los Angeles Abrasion Test at 42 and 30 percent for two concrete classes, while Georgia uses 45 and 45 to 65 percent for two classes.

Typical gradations for coarse and fine aggregate are shown in Figure 5-4. All types of rock and coarse sand muck can be processed simply by washing and screening to meet the gradation requirements. Thus, provided the muck satisfies abrasion, soundness, chemical and other requirements, little work remians to produce a useful product. The tests, such as chemical and abrasion tests, can be completed on soil and rock samples obtained during the subsurface exploration program.



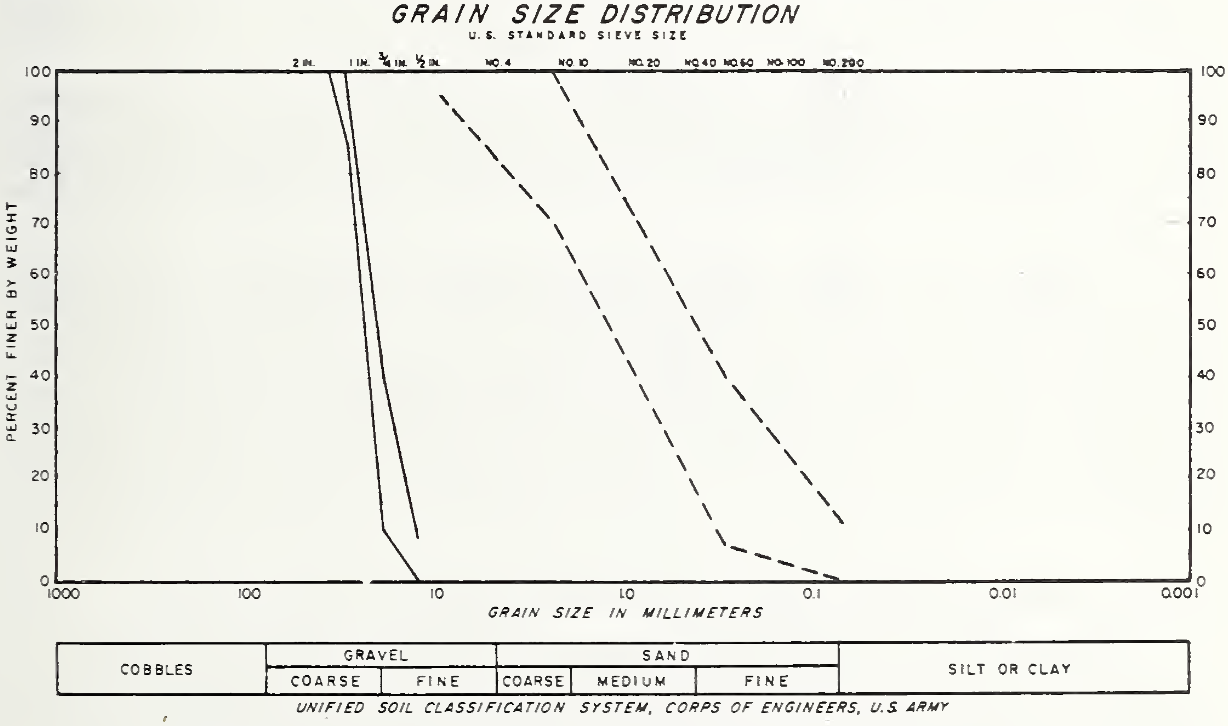
Symbol	Description
———	Limits for 1-1/2 in. Coarse Concrete Aggregate, Section M2.01.2
- - - - - -	Limits for Fine Concrete Aggregate, Section M4.02.02

FIGURE 5-4. TYPICAL GRADATIONS FOR CONCRETE AGGREGATES [5-3]

In a recent addendum to the ASTM specifications for aggregate (ASTM C33), the gradation requirements for fine aggregate have been relaxed, provided the aggregate satisfies all other criteria and a test specimen of concrete exhibits the required strength. This flexibility allows wider utilization of materials but requires more planning and engineering evaluation. In general, new sources of concrete aggregate must be carefully analysed for both physical and chemical acceptability in portland cement concrete. It is for this reason that concrete processors may be reluctant to change aggregate sources once they have established a reliable source.

5.3.5 Bituminous Concrete Aggregate

Asphalt paving mixtures may be produced from a wide range of aggregate combinations. The primary constituents besides asphalt are (1) coarse aggregate, (2) fine aggregate, and (3) mineral dust. Figure 5-5 contains some typical gradations of these constituents. Loads applied to the pavement by vehicle tires are carried by the framework of the stone or aggregate, which is held in place by the binding action of the asphalt. The suitability of aggregates for use in paving is determined by gradation, resistance to abrasion, soundness, cleanliness and purity, flat and elongated particles, surface properties and internal friction. Tunnel muck which meets the specified limits is an ideal source for paving aggregates, particularly since much of the initial crushing is completed during tunneling.



Symbol	Description
———	Limits for 1-1/4 in. Coarse Bituminous Aggregate, Section M2.01.3
– – – –	Limits for Fine Bituminous Aggregate, Section M3.11.04(B)

FIGURE 5-5. TYPICAL GRADATIONS FOR BITUMINOUS CONCRETE AGGREGATES [5-3]

Standard gradation specifications have been established (ASTM D692), but variations from the standards are usually permitted provided the change can be justified [5-15]. One reason for altering the mix is to produce a dense aggregate gradation with a minimum of voids. This improves strength and minimizes the volume of asphalt. Also, local aggregates which do not meet all tests may still be used based on local experience, as indicated below:

> "Special Local Aggregates. There are a number of local types of aggregate which often do not pass the standard tests but which make excellent asphalt mixtures because of certain inherent qualities. In areas where aggregates meeting standard tests are scarce, it often will be possible to use substandard materials if experience has shown them to be satisfactory or where research and testing warrant such use [5-16]."

The rock muck produced by a TBM operating in the Washington METRO was used for bituminous concrete aggregates. A detailed discussion of the material quality and its use is contained in Section 2 of this report. In order to utilize the muck, the processor had to screen out oversized rock, remove metallic and other types of debris, and crush the remaining material to a maximum particle size of 1-1/2 in. The crushing was required in order to eliminate the long, thin rock particles which are characteristic of TBM muck.

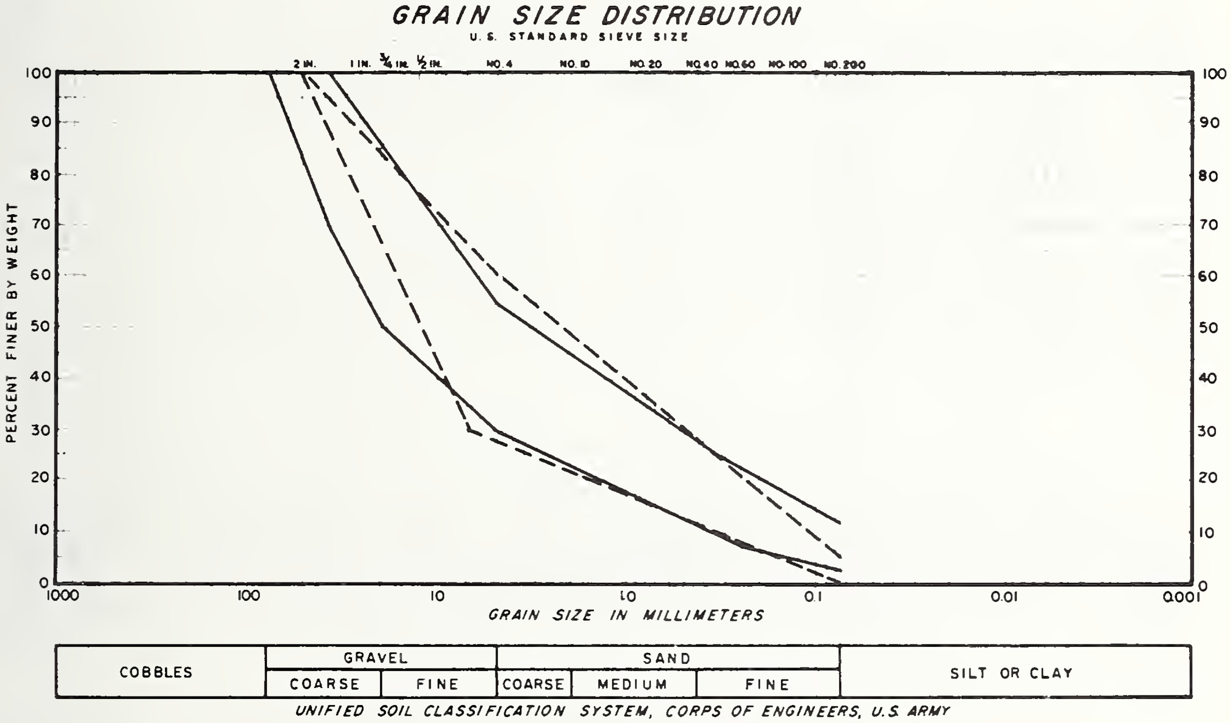
Additional crushing of rock muck or screening of sand and gravel muck can also produce acceptable fine aggregate. Natural sand deposits are the primary sources of fine aggregate. Once again, the material is screened and washed so that any construction debris would be removed.

Samples of the soil and rock deposits which will be excavated during construction can be obtained during the subsurface exploration program and tested for characteristics such as abrasion and chemical activity. Once the primary method of excavation has been determined, particularly for rock excavation, then estimates can be made of the amount of crushing or processing needed to produce an acceptable aggregate. Local processors can then be contacted to further evaluate the use or applicability of the muck aggregate in local pavement mixtures.

5.3.6 Pavement Base Course and Subbase Course

Crushed rock, crusher-run stone, crushed slag or cinders, or other processed materials are often required as a base course beneath pavements. In heavy duty highway pavements, the material must consist of hard durable stone which will not break up with repeated cycles of wetting and drying or freeze-thaw. Also as a result of the kneading action of wheel loads transmitted through the pavement to the base course the material must meet abrasion and soundness requirements similar to the requirements for bituminous concrete pavement aggregates. The gradation limits are wider in order to allow utilization of locally available materials. Typical base course gradations are shown in Figure 5-6. Tunnel muck which meets the basic chemical and soundness tests is an ideal source for base course materials.

Local gradations and materials used for parking lot and driveway base course may have less stringent requirements, appropriate for light duty traffic. In these cases, TBM muck may be suited for direct use in the pavement structure.



Symbol	Source
———	Massachusetts Highway Specifications, Section M2.01.7 [5-31]
– – – –	New York State Specification Part III, Item 42 [5-7]

FIGURE 5-6. TYPICAL GRADATIONS FOR BASE COURSE MATERIALS

5.3.7 Railroad Track Ballast

Railroad ballast is a high quality structural material. Some of its more important functions are listed below:

a. Distribute loads uniformly to the in-situ soils
b. Support the track structure (ties and rail) with a minimum of settlement and deflection
c. Provide good drainage for the track structure
d. Minimize dust
e. Prevent the growth of brush and weeds

In view of its importance, ballast is typically made from the highest quality materials available. Crushed stone is preferred because of its higher strength yielding increased frictional resistance and interlocking. Ballast generally varies in size from 0.5 in. A typical ballast section varies in thickness from 12 to 30 in. Soft, friable and deleterious materials are not permitted.

Since ballast must be a processed material, rock muck represents an ideal source. TBM muck normally contains long, thin rock particles which may require secondary crushing to produce the desired shape. Drill and blast muck would certainly require additional crushing. In both cases, however, the initial crushing or blasting has been completed during tunneling, thus reducing the remaining processing work.

5.3.8 Miscellaneous Uses

Several general uses for tunnel muck include slope protection, riprap, filler materials for gabions, and ingredients in loam. The details or specifications for each of these uses would have to be established to fit the needs of each project. Some general guidelines are given below:

5.3.8.1 Slope Protection

Crushed stone or screened stone has been used to stabilize earth slopes where drainage or erosion problems have developed. Screening of TBM or sand and gravel muck produces a coarse, free draining aggregate which is suitable for slope protection. In some highway applications, a green bituminous asphalt has been sprayed on the aggregate to provide interlocking and weed control and to blend the color with the typical green grass slope environment.

Aggregates have also been used as slope protection in drainage ditches and small streams not subject to intensive scour or wave action. These applications would depend on an analysis of the individual conditions [5-17].

5.3.8.2 Riprap

Riprap consists of large blocks of blast rock weighing up to 500 lb per block. The stone material is generally coarse, yet must be graded so that voids do not develop between major blocks. Voids would allow wave action to erode the underlying soils.

Drill and blast muck from large excavations might produce the required large, coarse rock needed for riprap. Tunnel work generally produces smaller blocks since muck handling becomes a restrictive problem. Rock muck has been successfully used as riprap in the Staten Island, New York, area and to repair sections of Rock Creek in Washington DC.

5.3.8.3 Gabions

Gabions are wire mesh boxes typically 4 x 1.5 x 1.5 ft which can be filled with stones and wired together to produce retaining walls or slope protection along water courses. Generally, the stones are limited to the maximum size that can be handled by manpower. TBM muck or screened drill and blast muck meet the general requirements.

5.3.8.4 Loam

Loam, as defined by the U.S. Department of Agriculture, is a combination of sand, silt and clay particles and does not contain organic materials. Specifically, the sand content varies from 25 to 52 percent by weight of the total sample, the silt content varies from 28 to 40 percent, and the clay content varies from 8 to 27 percent. Variation in these quantities outside the limits given above produces a soil such as sand loam, silt loam, or clay loam. All loam, as described above, provides an excellent soil base for plant growth.

It is important to note that the addition of organic soil to loam is not essential to plant growth although it is sometimes helpful. Organic soil is basically a soil conditioner rather than a fertilizer. It improves workability, moisture retention, and aeration, and can contribute to a favorable chemical environment.

Loam production is a feasible application for tunnel muck. One processor in the Washington D C area, combined concrete sand with silt and clay by-products from a screening and washing process, to produce a very useful loam. Combination of this material with readily available peat, muck or sewage sludge also provides a useful commodity.

5.4 GENERAL IMPROVEMENT TECHNIQUES FOR TUNNEL MUCK

The concept of improvement of tunnel muck includes all processes whereby the raw excavated material is altered either physically or chemically permitting it to be utilized in a more productive or specialized manner. The intended use of the muck controls both the particular method and degree of improvement. For example, debris may have to be removed from certain tunnel muck utilized for construction of landfill areas if it is intended to drive piles or install sand drains; on the other hand, very little debris may have to be removed if surcharging is used to stabilize the landfill.

Basic muck improvement techniques which may be easily implemented by the tunneling contractor involve sorting, crushing, screening, and washing. In many instances, it may be to the contractor's advantage to improve the muck characteristics by any of these methods in order to produce a more valuable commodity for commercial sale. All of the improvement techniques are applicable to rock, and sand and gravel-based muck, whereas sorting and possibly screening may be used to improve clay-based muck.

Methods for improving landfill areas composed of tunnel muck are described in Section 5.5. These improvement methods are in common use but generally require the services of a specialty contractor. Some of these methods, such as surcharging, however, can be implemented by the tunneling contractor.

5.4.1 Sorting

One of the most basic improvement techniques involves the removal, or sorting out, of unwanted materials from the raw muck. This unwanted material represents the debris portion of the muck (e.g. wood, steel, cement bags). Sorting of debris is quite often an essential step either for preparing the muck for processing through crushers or for utilizing the muck in a controlled type of filling operation.

Sorting methods can be divided into three types: (1) manual removal, (2) magnetic removal, and (3) mechanical separation.

Manual removal of material is probably the most effective means of sorting, but is also the most time consuming. Almost all types of debris can be removed by this technique. The operation can consist of a dozer operator assigned to rummage through the muck pile and pick up large, heavy debris pieces that could not otherwise be handled by manpower. Manpower can be employed to remove small debris pieces. Debris can be stockpiled and either removed to an appropriate disposal area or recycled. Depending on the magnitude of the sorting task, any number of dozers and manpower can be employed.

Separation of debris at the tunnel heading is an effective method of providing uncontaminated muck. However, the conditions at the heading, particularly in a drill and blast operation, are not conducive to sorting of small objects such as blasting wire and stemming materials. Cardboard boxes, cement sacks, drill rods, and discarded reinforcing bars can be set aside in a disposal container mounted on the drill jumbo. This effort would greatly improve the muck quality.

Magnets can be an effective means to remove metallic objects. Such a device, for example, can be mounted on a conveyor belt used to transport the muck. However, the magnet would be virtually useless in attempting to remove metals covered by several feet of soil or rock.

Mechanical separation devices such as the one illustrated in Figure 5-7 are a third type of sorting technique, and are best suited for removing wood and other types of lightweight materials from sand and gravel sized muck. Materials having a specific gravity less than 1.6 can be easily removed from sands and gravels which commonly have higher specific gravities, in the range of 2.6 to 2.65 [5-18]. Clay and silt size muck, which tends to stay in suspension in water, would be difficult to sort using the separation device.

Operation of the separation device shown in Figure 5-7 involves feeding the muck to a perforated plate by way of a conveyor belt. The feeding is arranged to spread the muck into a thin blanket of material across the plate. Water, which is continuously circulated in a clockwise direction, travels upward through the holes in the plate, carrying away the lighter materials permitting the heavier materials to fall off the end of the steeply sloped plate. The cycle is completed by recirculating the water and directing the debris material through an exit for removal. The excavated material, cleaned of debris, falls to a storage bin below the separator.

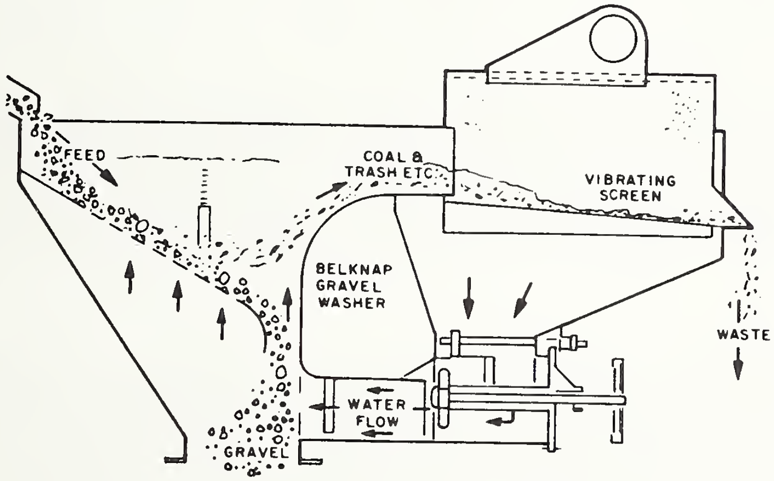


FIGURE 5-7. MECHANICAL SEPARATION DEVICE [5-18]

SOURCE: TAYLOR; p. 10

5.4.2 Crushing

Excavated rock, sand, and gravel that is oversized for a particular use can be reduced in size by processing the material through a crusher machine. Crushing is also an effective means to alter rock texture from smooth to angular.

The crushing characteristics of rocks are related to their fabric, grain size, grain shape, orientation, interlocking of particles, and packing. These characteristics control the ease with which crushing occurs and the shape, size and texture of the finished product. For example, a rather dense rock with tight grain interlocking usually produces a competent crushed stone material of a suitable size and hardness. On the other hand, a rock structure which has a rather weak grain interlocking is easy to crush, but the final product shows excessive granulation. Many of the crushing characteristics mentioned can be determined by microscopic observation of an intact rock sample. After establishing as many crushing characteristics as possible an estimate can then be made of the feasibility of producing, for example, a suitable crushed stone product.

Crushers are generally classified according to the stage of crushing which they accomplish as primary, secondary, and tertiary. Some common types of crushers and their uses are given below:

Primary Crushers	Secondary Crushers	Tertiary Crushers
Jaw	Cone	Roll
Gyratory	Roll	Rod Mill
Hammer Mill	Hammer Mill	Hammer Mill

The jaw crusher is one of the most widely used primary crushers. It consists of two jaws, one stationary and the other movable. The crushing action is developed when the movable jaw swings towards the stationary jaw. The distance between the two jaws reduces from top to bottom and the crushed stone travels downward under the influence of gravity until it is finally small enough to exit through the bottom opening. This device is particularly efficient for extremely hard rocks.

The gyratory crusher consists of a heavy cast iron frame with a vertical central shaft which carries a truncated cone. As the shaft and crushing head rotate, the eccentric support at the base of the shaft causes a gyrating motion to occur. The crushing action of the gyratory crusher does not vary much from the jaw crusher. Some additional bending stresses are imparted to the rock from the curved liner plates and truncated cone crushing part. There is also a greater grinding effect in the gyratory crusher due to the freedom of movement of the particles within the truncated cone.

Cone crushers are very similar to the gyratory crushers with the following exceptions:

a. Shorter cone

b. Smaller receiving opening

c. Rotates at higher speeds (430-580 rpm)

d. Produces more uniform material

The hammer mill is an impact type of crusher. The main parts consist of a housing frame, a horizontal shaft extending through the housing, a number of arms and hammers attached to a spool which is mounted on the shaft, and a series of grate bars through which the crushed stone falls. As the stone enters the mill, it is crushed first by the hammers which travel at high speed, and second, by being forced against the breaker plates.

Roller crushers are of two general types, single roll and double roll. The single roller is generally considered a primary crusher.

The slug roller is a device with a set of projected slugs or teeth extending from the roller which bite into the rock and provide a hammer type action against the rock on the curved plates opposite the roller. The single roller crusher is generally used on softer rock such as limestone when it is desired to make a maximum single reduction with one machine.

Double roller crushers consist of two rollers placed side by side which travel in opposite directions (toward each other). The maximum sized stone that can be fed into a double roller crusher is basically controlled by the distance between the two rollers and the diameter of the rollers [5-19].

Both the rod mill and ball mill are used to produce fine aggregate such as sand. These devices are almost always used after a stone has been suitably crushed through other devices. In the rod mill, long small diameter rods are placed inside a mill which rotates slowly. The tumbling action of the rods produces the desired grinding effect. A ball mill is basically the same set up except steel balls replace the rods.

5.4.3 Screening

The screening process enables the separation of a material into different small size ranges. This operation permits the fabricating of a particular sized material which, for example, meets a required gradation specification. The screening process is also an integral part of the many crushing operations described previously providing a means for selectively removing certain stone sizes from the crushing cycle.

Screens are primarily a criss-crossed arrangement of strands, usually wire. A variation of the screen known as a grizzle is a series of parallel bars equally spaced. Screens are generally designated by the size of the openings. Screen openings greater than 3/8 in. are generally designated by the actual size of the opening (i.e. 1/2 in., 2 in., 4 in. etc.). For openings less than 3/8 in., a mesh number is assigned to the particular size opening. Table 5-9 gives two different screen classification systems.

After a material has been screened it is commonly referred to as undersized material if it passed through the screen openings, and oversized if it was retained on the screen. For example, material passing the 1/2-in. screen is designated -1/2 material (undersized), and material retained is designated +1/2 material (oversized).

Two basic types of screens are in common use today, revolving and vibrating. Revolving screens are generally cylindrical in shape and have their longitudinal axis set at a small angle usually not more than 10 degrees. As material is fed into the revolving screen, the slow rotating action aids the screening process.

The vibrating screen is a flat screen usually set into a steel frame capable of holding more than one such screen. The screens are vibrated by means of an eccentric shaft, a counterweight shaft, or an electromagnet directly attached to the frame or to the screens. The screens are usually positioned at a slight angle and are set up in a multi-deck unit with openings arranged progressively smaller from top to bottom.

TABLE 5-9. SCREEN CLASSIFICATION SYSTEMS [4-1]

SOURCE: LAMBE; p. 31

Tyler Standard				U.S. Bureau of Standards		
Mesh Number	Opening in.	Opening mm	Wire Diameter, in.	Mesh Number	Opening in.	Opening mm
..	3.0	76.2	0.207	..	4.00	101.6
..	2.0	50.8	0.192	..	2.00	50.8
..	1.050	26.67	0.148	..	1.00	25.4
..	0.742	18.85	0.135	..	0.750	19.1
..	0.525	13.33	0.105	..	0.500	12.7
..	0.371	9.423	0.092	..	0.375	9.52
3	0.263	6.680	0.070	3	0.250	6.35
4	0.185	4.699	0.065	4	0.187	4.76
6	0.131	3.327	0.036	6	0.132	3.36
8	0.093	2.362	0.032	8	0.0937	2.38
9	0.078	1.981	0.033	10	0.0787	2.00
10	0.065	1.651	0.035	12	0.0661	1.68
14	0.046	1.168	0.025	16	0.0469	1.19
20	0.0328	0.833	0.0172	20	0.0331	0.840
28	0.0232	0.589	0.0.25	30	0.0232	0.590
35	0.0164	0.417	0.0122	40	0.0165	0.420
48	0.0116	0.295	0.0092	50	0.0117	0.297
60	0.0097	0.246	0.0070	60	0.0098	0.250
65	0.0082	0.208	0.0072	70	0.0083	0.210
100	0.0058	0.147	0.0042	100	0.0059	0.149
150	0.0041	0.104	0.0026	140	0.0041	0.105
200	0.0029	0.074	0.0021	200	0.0029	0.074
270	0.0021	0.053	0.0016	270	0.0021	0.053
400	0.0015	0.038	0.001	400	0.0015	0.037

5.4.4 Washing

It is sometimes necessary to remove a film of material from the muck prior to final processing. When excavating a glacial till material, for example, clay or silt films commonly occur by adhering to the larger granular sized particles. Excavation of rock by tunnel boring machines often produces a slurry material which can leave a film on the rock pieces. A film can also result during the crushing process when dust size particles coat the crushed rock. These films are particularly harmful when the rock is to be used for concrete aggregates in which a good bond is required between aggregate and cement.

A common procedure for washing involves jet sprays which direct water over a thin bed of material. This procedure is oftentimes performed in conjunction with the screening operation. The terms 'dry screening' or 'wet screening' are often used to further describe the type of screening operation utilized. While not the primary use, the separation technique illustrated in Figure 5-7 can also be employed as a method of washing.

5.5 METHODS TO IMPROVE ENGINEERING PROPERTIES OF LANDFILLS

As indicated in previous sections of this report, tunnel muck is suitable for use in landfill projects. In order to safely support structures, suitable muck and proper methods of placement are required to complete a landfill area. Several techniques presently used in the foundation construction industry can be applied to improve unsatisfactory landfill areas. The improvement methods have been developed to accomplish one or more of the following:

a. Improve soil shear strength

b. Reduce potential settlement under load

c. Secure a more watertight condition

Almost all the methods involve some form of material compaction.

The remainder of this section describes some of the various techniques available for improving landfill areas consisting of tunnel muck.

5.5.1 Improvement Methods Applicable to All Types of Muck

5.5.1.1 Compaction

The primary objective of compaction is to increase soil density, i.e. weight per unit volume. The mechanism of compaction involves the reduction of void ratio by one or more of the following methods: (1) reorientation of the particles, (2) fracture of the grains or bonds between them, followed by reorientation, and (3) bending or distorting of the particles and their absorbed layers [5-20]. Compaction of granular materials is generally accomplished by reorientation of the grains which is resisted by the friction between particles. Fine-grained soils undergo both a reorientation and a distortion process which break down the attractive cohesion forces acting between particles.

The addition and removal of water is an effective means for aiding the compaction process. For fine-grained soils water reduces particle cohesion, while in granular soils water tends to reduce the capillary tension between particles, thus decreasing the friction forces. Water also acts as a lubricant between particles, particularly in granular soils, permitting higher densities when the water-soil mixture is compacted. Figure 5-8 shows a typical relationship between moisture content and density.

The maximum density occurs at a point corresponding to the optimum moisture content. When water is added beyond the optimum moisture content, the water begins to separate the soil particles, thus decreasing density. The zero air voids line (ZAV), or 100 percent saturation line, represents the limit for any point on the moisture content-density curve.

The density versus moisture content curve can be determined in the laboratory [5-21]. Density is commonly expressed as dry unit weight. Some typical laboratory moisture content-density curves for various soil types are given in Figure 5-9.

These laboratory curves can be used to numerically evaluate the amount of compaction obtained in the field. Contract documents usually specify the degree of field compaction by designating that a particular minimum percentage (e.g. 95 percent) of laboratory dry unit weight must be obtained. The following percentages of laboratory dry unit weights, determined by ASTM D1557, are generally recommended for various uses:

Use	Percent of Laboratory Dry Unit Weight
Airfields	100
Structural fill for support of buildings	95
Parking lot areas	92
Subgrade	85 - 90

Compaction techniques can be divided into two basic groups: (1) surface compaction methods and (2) compaction at depth. The objectives are similar for both, but the techniques differ. Compaction at depth is primarily an in-situ technique to be applied to a large soil mass; surface compaction is concerned with densifying relatively small layers of soil as they are being placed. Methods for compaction at depth, such as vibroflotation, blasting, and compaction piles are discussed in subsequent parts of this section. The remainder of this section contains descriptions of surface compaction methods.

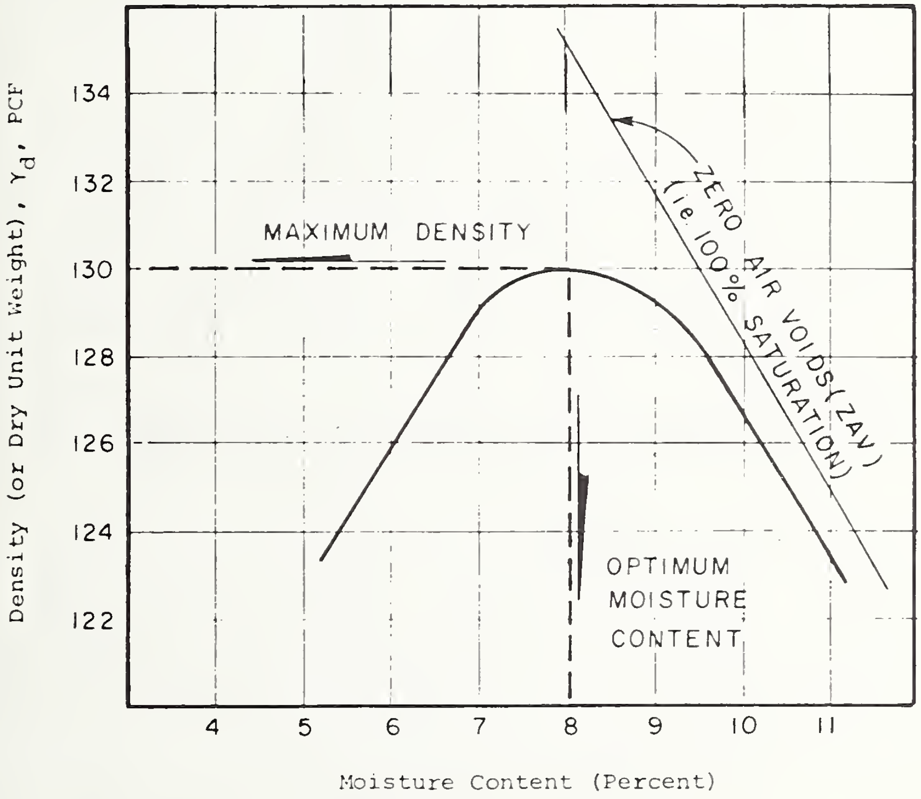
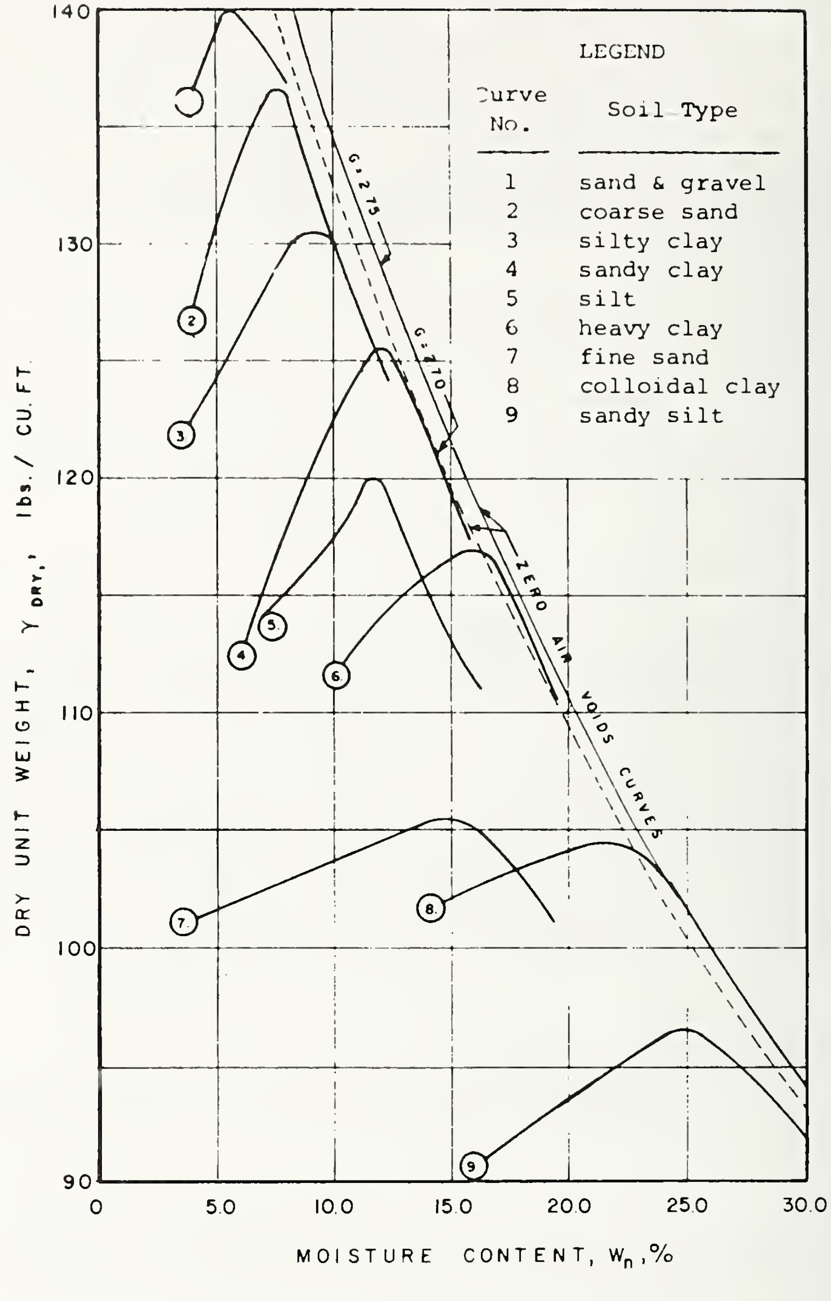


FIGURE 5-8. TYPICAL DENSITY VERSUS MOISTURE CONTENT CURVE



Note: All tests by ASTM 1557-64T, Method C for Curve 1, Method A for all other curves.

FIGURE 5-9. LABORATORY DENSITY VERSUS MOISTURE CONTENT CURVES FOR VARIOUS SOIL TYPES [5-22]

SOURCE: HOUGH; p. 512

5.5.1.2 Surface Compaction Methods

The process of surface compaction consists of placing a designated thickness of material over an area and then applying a compactive effort to obtain the desired material density. As a general rule, the cost of placing and compacting the soil decreases as lift thickness increases. In this respect it is more economical to use the maximum practical lift thickness. Since a definite density gradient can be expected within a lift, the thickness of the lift depends largely on obtaining a certain minimum density throughout the entire lift. In addition, the particle size of the material used for compacting influences the lift thickness. It would be unsatisfactory to specify an uncompacted lift thickness of 8 in. if the maximum size of the material being used is 10 or 12 in. An uncompacted lift thickness of 8 in. is generally specified in order to obtain high-density requirements, i.e. greater than 95 percent compaction.

There are four basic methods available for compacting soils: kneading action, static weight, vibration and impact. Several machines are available which utilize one or more of these methods. Some of the common types of machines are tamping rollers, smooth-wheel rollers, pneumatic tired rollers, vibrating rollers, self-propelled vibrating plates, manually propelled vibrating plates, and manually propelled compactors. The particular method, machine, and procedure to be used largely depends on the soil type being compacted. Table 5-10 can be used as a guide to determine the most suitable surface compaction method for various soil or muck types.

In general, vibratory compaction methods are used on granular soils [5-23]. Under vibration, the particles shift their position and the soil mass becomes denser. D'Appolonia reports that lift thicknesses over 5 ft may be compacted when using heavy vibratory units [5-24].

Tamping rollers are of the sheepsfoot type or some modification thereof. The roller consists of a hollow steel drum with an arrangement of projecting steel feet. The weight of the unit can be varied by adding water or sand to the drum. The roller, either self-propelled or towed by a tractor, moves over the surface. Initially the feet penetrate the entire lift thickness producing a kneading action and a pressure sufficient to compact the soil. Compaction of the lift proceeds from the bottom to the top at which point the feet are "walking" on top of the compacted lift. This device is a popular machine for compacting clay-based materials.

Modifications of the sheepsfoot roller are the segmented pads or grid. The modifications describe the configuration of the projecting feet from the drum.

The smooth wheel rollers are generally classified by type or weight. On many construction sites, any vehicle having sufficient weight, such as a 10-wheel dump truck or traxcavator can be employed for compaction purposes. As in all of the compaction machines, a systematic compactive effort consisting of a designated lift thickness compacted by a certain number of coverages by the machine, produces best compaction results.

Another common compaction machine which employs a kneading action is the pneumatic roller. This machine takes advantage of the heavy static machine weight and the high tire-to-ground contact pressures.

TABLE 5-10. SUITABLE TYPE OF COMPACTION FOR DIFFERENT SOIL GROUPS [5-24]

SOURCE: BROMS & FORSSBLAD

Type of compaction equipment	Rock fill	Sand and gravel		Silt, silty soils clayey sand and clayey gravel		Clay	
		Well-graded	Uniformly graded a)	Silty sand, silty gravel	Silt, sandy silt, clayey sand, clayey gravel	Low or medium strength b)	High strength
Static smooth-wheel rollers 1), 3-15 tons	-	x	x	x	x	x	-
Vibrating smooth-wheel rollers 2), 3-5 tons	x	x̲	x̲	x	x	x	-
Vibrating smooth-wheel rollers 2). 10-15 tons	x̲	x̲	x̲	x̲	x	-	x
Vibrating plate compactors, 0.1-0.5 tons	-	x̲	x̲	x	x	-	-
Vibrating tampers, rammers, 0.05-0.1 tons	-	x	x	x	x	x	x
Rubber-tired rollers 2), 10-50 tons	-	x	x	x̲	x̲	x̲	-
Sheepsfoot rollers 2) 3), 5-30 tons	-	-	-	-	x	x	x̲
Pad-type rollers 2) 3), 5-30 tons	-	x	x	x̲	x̲	x̲	x
Grid-type rollers 2), 5-15 tons	x	x	x	x	x	x	-
Crawler tractors, 10-30 tons	x	x	x	x c)	x c)	x c)	-

LEGEND

1) Self-propelled

2) Tractor-drawn or self-propelled

3) Static or vibrating

a) Self-propelled rollers often do not have sufficient traction on uniformly graded sand and gravel.

b) Crawler tractors are often used at high water contents and very low strength.

c) Compacted at higher water content than the optimum water content determined by Proctor compaction tests.

x can often be used
x̲ recommended

5.5.1.3 Surcharging

Almost every type of compressible soil including all types of tunnel muck can be densified by a static weight. When a temporary static weight (expressed as a weight per area or unit load) exceeds a final design unit load, the excess unit load represents a surcharge. Figure 5-10 illustrates this concept. Placement of the surcharge load for a sufficient length of time ensures that the underlying soils have been stressed to a level higher than that expected from the final permanent loading. Newmark and others [5-25] have developed theoretical equations and design charts for determining the extent of stress increase at various depths resulting from a surface loading. As the result of surcharging, settlements of the area caused by the final design load will be less severe.

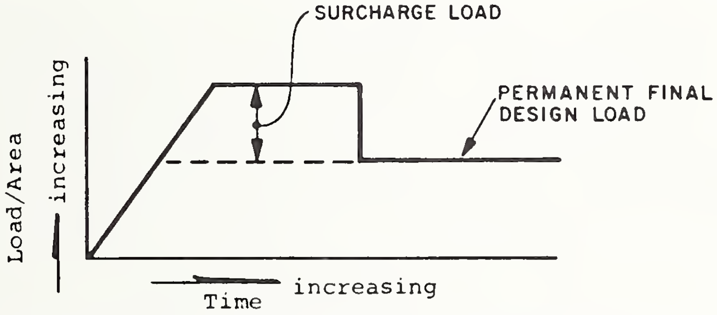


FIGURE 5-10. SURCHARGE LOADING DIAGRAM

The surcharge load must therefore be left in place long enough to allow sufficient consolidation or compression of the underlying soft soils. This time factor is a function of the rate of consolidation which is dependent on the soil permeability, thickness of compressible layer, and the location and size of drainage paths. Terzaghi and Peck [4-2] give a detailed explanation of the theory of rate of consolidation applicable to all soil types.

In concept, as loads are placed on a compressible soil, excess pore pressure in the pore water develops and with time this excess pressure dissipates, accompanied by consolidation. Coarse-grained materials can dissipate the excess pore pressure relatively fast due to the large pore spaces between grains. On the other hand, fine-grained soils dissipate the excess pore pressure at a much slower rate. The time required to consolidate fine-grained soils can be reduced by installing sand drains or artificial drainage channels in the soil.

Methods available for applying the static weight force to the compressible soil include earth fills, water loading by tanks, ground water lowering, anchors or jacks, and vacuum methods. Depending on the strength of the compressible soil, the loading may be applied instantaneously. In some instances, quick loading on very weak soils may cause serious stability problems and may even result in the formation of mud waves [3-32]. This problem can usually be avoided by implementing a phased loading program. Placing of a portion of the final load permits the soil to gain strength by consolidating after which additional portions of the surcharge may be applied. The procedure is repeated until the complete surcharge load has been reached.

Design of a surcharging program requires the determination of the final surcharge load and the period of time for the surcharge to remain in place. In addition to defining the vertical and horizontal limits of the compressible soil, its physical characteristics, such as permeability, and consolidation, must be obtained. The amount of time needed for the surcharge to remain in place can be estimated from theory of consolidation and from methods of analysis developed for surcharging with sand drains [5-26].

Field monitoring of the consolidation process is an effective means for controlling the length of time the surcharge should be left in place. This typically involves the installation of settlement platforms (or points) placed prior to the surcharge load. Such devices are usually placed at the top of the compressible soil, but for thick layers, internal devices are commonly installed. A continuous plot of settlement versus time during surcharge load can be used to help determine the actual time for removal of the surcharge.

Three case studies utilizing surcharge as a densification method can be found in an article by Johnson [5-26].

5.5.1.4 Soil Stabilization

The process of improving a soil's physical and/or chemical properties is known as soil stabilization. Soil stabilization methods include compaction, drainage, surcharging, and protection of the surface from erosion and moisture infiltration. In more recent years, however, soil stabilization has more often referred to soil improvements which alter the soil material by changing its composition.

The particular type of soil and its deficiencies determine both the mode and degree of alteration. All of the methods, however, are related to improving strength, compaction, and/or permeability. Soil stabilization methods can be divided into two categories: mechanical stabilization and stabilization by additives (usually chemicals).

Mechanical stabilization is the improvement of a soil by changing its grain size distribution (i.e. gradation). This can be accomplished by either blending two or more different soil gradations into one composite mixture or by removing select ranges of particle size from one soil.

For purposes of mechanical stabilization, soil can be conveniently divided into two different particle size groups. The aggregate portion consists of predominantly bulky grains typically larger than some arbitrary limit (e.g., No. 40 or No. 200 sieve size). The binder is the finer fraction which includes both small bulky grains and clay size particles. The aggregate provides internal friction to the soil mass which results from the particle to particle contact forces developed under a normal force. The plasticity of the binder material supplies cohesion and imperviousness to the soil mass. The best binders are typically finer than No. 40 size with a liquid limit less than 40 percent and a plasticity index (liquid limit minus plastic limit) between 5 and 15 percent [5-20]. Montmorillonite clays should be avoided as a binder due to their swell potential and extreme frost susceptibility.

The engineering performance of a mechanically stabilized compacted soil can be determined by adjusting the relative proportions of aggregate and binder. The optimum material is obtained when a sufficient amount of binder exists to completely fill the voids without destroying the grain-to-grain contact of the aggregate particles. A soil almost completely free of binder will be relatively incompressible and free from frost susceptibility; however, it will have a high permeability. Added amounts of binder material, which can fill the void spaces, will decrease permeability but will also slightly increase compressibility and frost susceptibility. The binder material also increases the bulk unit weight of the soil mass. Too much binder material can result in a sharp drop in internal friction and a small increase in cohesion, but can cause much greater compressibility and a potentially serious problem with frost susceptibility.

A number of methods can be used to determine the optimum design of a mechanically stabilized soil. Probably the most convenient method involves duplication of a particular gradation curve on which past performance records have been established. One disadvantage of this method of design is that the standard curves do not consider the effects of grain shape or the volume of water absorbed by the binder material. A more rational design method involves separating the aggregate and binder portions of the soil and compacting them separately to determine the volume of voids in the compacted aggregate and the density of the compacted binder. The mix can then be proportioned such that the total binder (from all ingredients) is from 75 to 90 percent of that required to fill the voids. Typically, the maximum strength can be obtained with a minimum of 20 to 27 percent of total binder. This minimum amount is usually less than that required to obtain maximum density [5-20].

Three types of mechanical stabilization methods are described in a text book edited by Leonards [5-27]: (1) addition of binder to gravel for road construction, (2) addition of material to reduce permeability, and (3) removal of fines from gravel. This book also includes some standard gradation curves that have been developed by AASHO.

The most common application for soil stabilization by additives has been to improve soils for highway and airfield pavements. Common additives include cement, bitumen, lime, salt, chloride, lignin and chrome-lignin. Additives may be used in almost any type of soil, but certain additives are more suitable for some soils than for others. For example, lime is best suited for stabilizing fine-grained soils.

In most cases, large bulky materials, such as blasted rock, which can have particle sizes over 12 in. cannot be stabilized by additives.

The design process typically consists of the following steps: (1) select stabilizer, (2) determine the amount and method of application, and (3) determine the amount of soil to be stabilized. Design charts are available for determining the type and amount of additive to be used. In many instances the performances of trial mixes may have to be verified in the laboratory to help in the final selection of a design mix. The laboratory test program should simulate the field conditions as accurately as possible.

Construction techniques, while they may differ slightly for various additive types, generally consist of the following steps: (1) preparation of the soil subgrade, (2) addition of water and additives to the soil, (3) mixing, (4) spreading and compacting, (5) finishing, and (6) curing.

Addition of water and additives to the soil (step 2) and mixing (step 3) are the field procedures which can have the greatest effect on the performance of the final stabilized soil. Design is based on an accurate measure of the various soil additive materials. Consistent performance throughout the stabilized soil mass depends on this fact. Mixing can be difficult, particularly when dealing with fine-grained soils. Lumping of these materials is oftentimes a problem. Leonards [5-27] gives some suggestions to improve the mixing process.

The following comments provide general information on the most common additives used for soil stabilization. References [5-28, 5-29] should be consulted for more detailed information.

Cement is perhaps the most widely used and cheapest soil stabilization additive. Just as in a concrete mix, the cement acts as a bond between soil aggregate particles [5-30].

Experience has shown that a well-graded soil having less than 50 percent of its particles finer than a No. 200 sieve (i.e. 0.074 mm) and a plasticity index lower than 20 percent is the best soil material for cement stabilization [5-27].

The addition of cement to soil will generally have the following effects:

a. Increase unconfined compressive strength

b. Decrease soil plasticity

c. Increase durability in feezing and thawing (but mixture still vulnerable to frost effects)

The amount of cement needed for stabilization depends on the soil type. Granular materials such as gravels typically require 5-10 percent cement; clays generally need 12 to 20 percent cement. Table 5-11 indicates ranges of unconfined compressive stengths for various soil types stabilized by 10 percent cement.

TABLE 5-11. UNCONFINED COMPRESSIVE STRENGTHS FOR VARIOUS SOILS STABILIZED WITH TEN-PERCENT CEMENT [5-27]

Soils	Compressive Strength (psi)
1. Plastic clay, organic soil	<50
2. Silt, silty clay, very poorly graded sand, slightly organic soil	50-150
3. Silty clay, sandy clay, poorly graded sand and gravel	100-250
4. Silty sand, sandy clay, sand, gravel	250-500
5. Well-graded sand-clay, gravel-sand-clay mixture, sand, gravel	450-1,500

SOURCE: LEONARD; p. 377

The most widely used bitumens for soil stabilization are (1) asphalt and (2) tar. Normally, the straight run asphalt is too viscous for adequate workability and is made more fluid by (1) heating, (2) emulsifying in water, or (3) cut-back with a solvent (e.g. gasoline, naptha).

The addition of bitumen can provide one or more of the following benefits:

a. Provide stength to clean cohesionless soils which lack sufficient binder material

b. Stabilize the moisture content of fine-grained soils

c. Provide waterproofing to materials having only frictional strength

Amount of bitumen materials needed for stabilization is generally less than 10 percent. Three to five percent are required to stabilize sandy soils, and greater amounts, 6 to 8 percent, are required for fine-grained materials. Almost any soil mixed with bitumen can be used for stabilization, but most desirable soils have the following characteristics [5-27].

a. Maximum particle size less than 1/3 compacted thickness of the treated soil

b. Greater than 50 percent of the soil particles finer than No. 4 sieve (4.76 mm)

c. From 35 to 100 percent of the soil particles finer than No. 40 sieve (0.42 mm)

d. Greater than 10 percent but less than 50 percent of the soil particles finer than No. 200 sieve (0.074 mm)

e. Liquid limit less than 40 percent

f. Plasticity index less than 18 percent

Two different mechanisms have been used to describe the stabilization of soils by bitumen: (1) binding soil particles together, or (2) protecting soil from the deleterious effects of water (waterproofing). Cohesionless soils are primarily affected by the first mechanism, while water sensitive cohesive soils are affected by the second.

Hydrated lime is another common soil additive, used quite frequently on fine-grained soils. It is effective in: (1) decreasing the plasticity index of high plasticity soils, (2) reducing maximum compacted density with an increase in the optimum moisture content, and (3) increasing strength. Figure 5-11 shows the effect of lime on the compaction characteristics of two different clays.

The following case study illustrates the potential use of soil stabilization methods for improving tunnel muck characteristics.

Open stoping is the anticipated mining excavation method for recovering copper-bismuth in the Warrego Mine in Northern Territory, Australia. In the early 1970's, a laboratory research program was initiated to investigate the possibility of backfilling the primary stopes, up to 20 m wide and 150 m high, to enable full recovery of the ore pillars [5-31]. The laboratory testing program and subsequent model test program were concerned with mechanical and chemical stabilization of available fill materials to evaluate their suitability as backfill material. Strength and durability of the stabilized fills were determined, and model tests helped to determine procedures for fill placement.

The laboratory program was divided into two parts. First a thorough testing program was conducted to determine the essential chemical and physical properties of the proposed fills. The following tests were performed on mine fills that were subjected to mechanical and cement stabilization:

Physical Tests	Chemical Tests
Density Determinations	Water Analysis
Gradation Analysis	Immersion Tests
Sedimentation Analysis	
Unconfined Compression Tests	

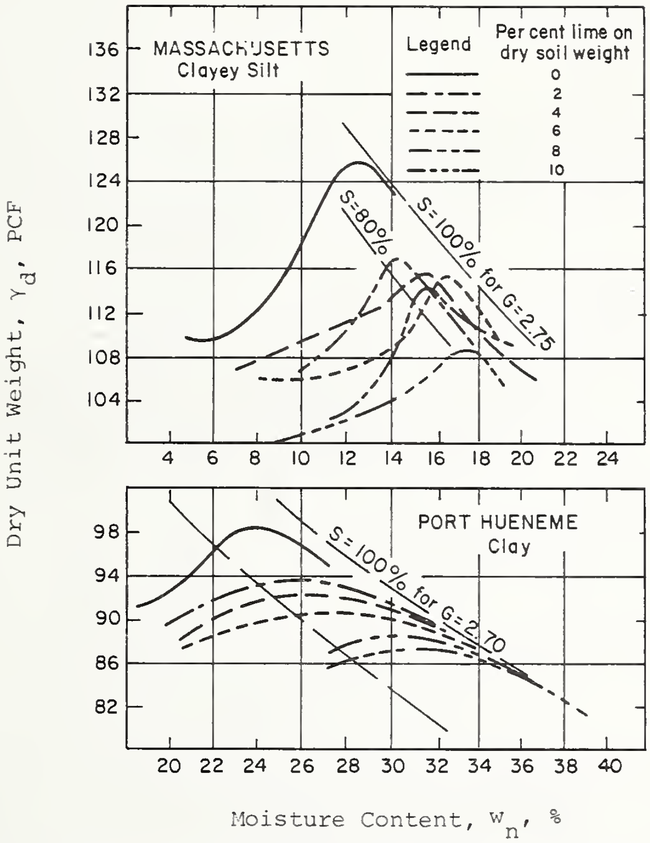


FIGURE 5-11. EFFECT OF LIME ON COMPACTION CHARACTERISTICS OF CLAY [5-27]

SOURCE: LEONARD; p. 399

Mechanical stabilization consisted of either the addition of up to 10 percent fines or the fractionation and recombination of selected fractions with the object of increasing the bulk density. Cement stabilization consisted of treating the mine fills with one of the following: 4 percent or 2 percent cement, 2 percent cement plus 2 percent tailings, or 2 percent cement plus 2 percent flyash.

The second part of the laboratory program involved a series of seven model filling tests for determining the effect of moisture content, grading, and cementation on the performance of the fill.

Two different fill materials, supplied by Peko Mines, were used in the laboratory program; a sandy gravel called Wisco Gravel, and Warrego Mine Tailings. Figure 5-12 shows some typical strength data obtained on the chemically stabilized Wisco gravel.

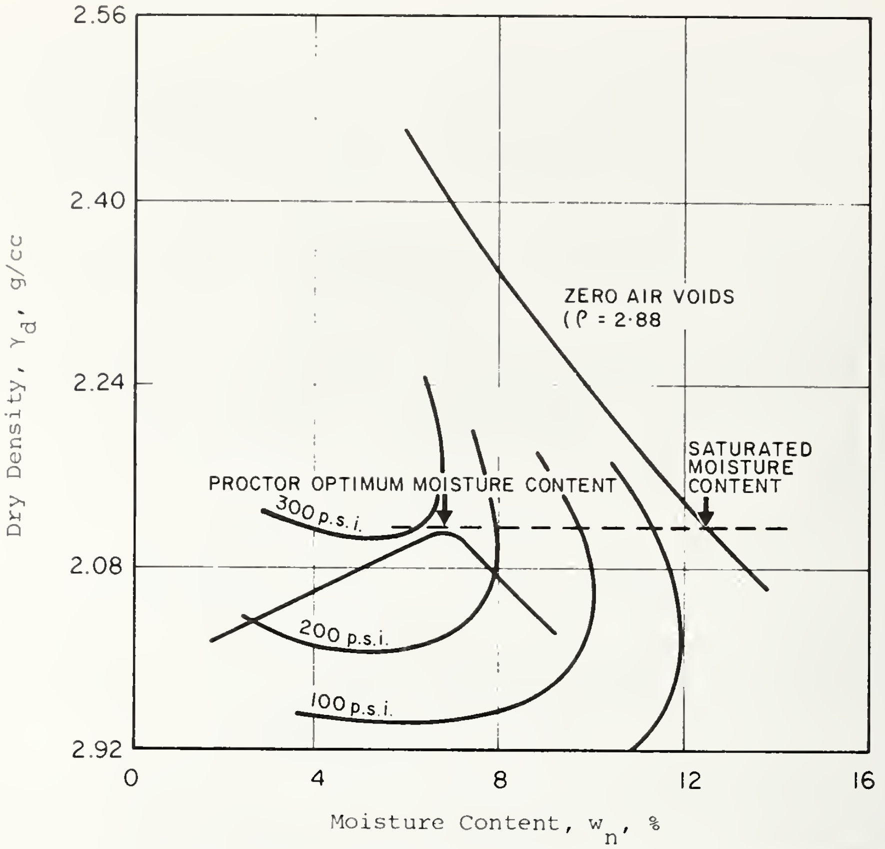


FIGURE 5-12. STRENGTH DATA FOR WISCO GRAVEL STABILIZED WITH FOUR-PERCENT CEMENT [5-31]

SOURCE: INGLES

Some of the conclusions obtained from the laboratory test program were:

a. Mechanical stabilization has little practical value for the fills tested.

b. Cement stabilized fills must be placed wet.

c. Wet cement fills are best placed at a moisture content wetter than optimum.

d. The maximum strength of wet cement fills occurs over a limited range of water content.

e. The fill materials need to be of free draining quality.

f. When using wet fill methods, there is no substantial economy of cement usage. It is recommended that a safety factor of five be used when using conventional laboratory tests of cement-treated fill to estimate actual fill performance in the field.

g. Untreated dry fill can be used provided that a suitable side-grouting system can be implemented.

5.5.2 Improvement Methods Applicable to Coarse-grained Muck

5.5.2.1 Vibroflotation

Vibroflotation is a method for compacting in-situ sand and gravel materials above or below the water table and to depths as great as 70 ft. The technique was introduced into the United States in 1939 after its first reported use in Russia in 1936.

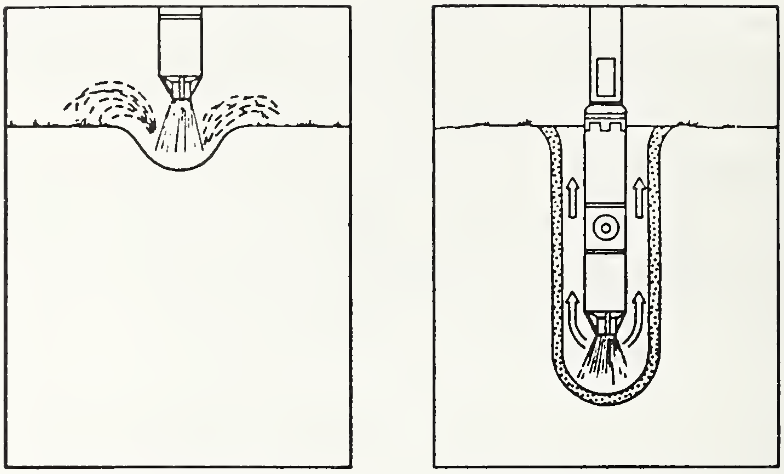
The vibroflot device is a hollow cylindrical penetrator. One particular model weighs approximately two tons and measures 6 ft long by 15 or 17 in. in diameter. The bottom of the vibroflot contains an eccentric weight capable of operating at 1800 rpm to produce a horizontal centrifugal force of 10 tons. Spouts at the top and bottom provide for jet water flow. In operation, the vibroflot is usually hung vertically from a crane.

Figure 5-13 illustrates the vibroflotation technique of sand densification. Briefly, water jets out of the bottom of the vibroflot faster than it can drain away from the soil. A 'quick' soil condition results, and the vibroflot can be simultaneously sunk into the soil until the desired compaction depth is attained. After switching the water flow to the top jets and reducing the pressure of flow, backfill material is continuously fed into the vibroflot hole causing water to flow to the surface. The operation is completed by withdrawing the vibroflot to the surface, at a typical rate of one foot per minute, accompanied by the continuous feed of backfill material. The mechanical vibration of the vibroflot and simultaneous application of water nullify the effective stresses between the soil grains which are rearranged unconstrained and unstressed to the densest possible state [5-32].

Figure 5-14 shows the range of soil particles most suitable for densification by the vibroflotation technique as recommended by the Vibroflotation Company [5-33]. The sampling of gradation curves presented previously in this report for TBM, drill and blast, and sand and gravel muck indicates that a very high percentage of the curves fall within the limits established in Figure 5-14. It therefore appears that most granular muck can be improved by vibroflotation techniques. Actual field tests have shown that vibroflotation can be performed on silt and clay materials [5-34] (refer to stone column method described in Section 5.5.3.1 of this report).

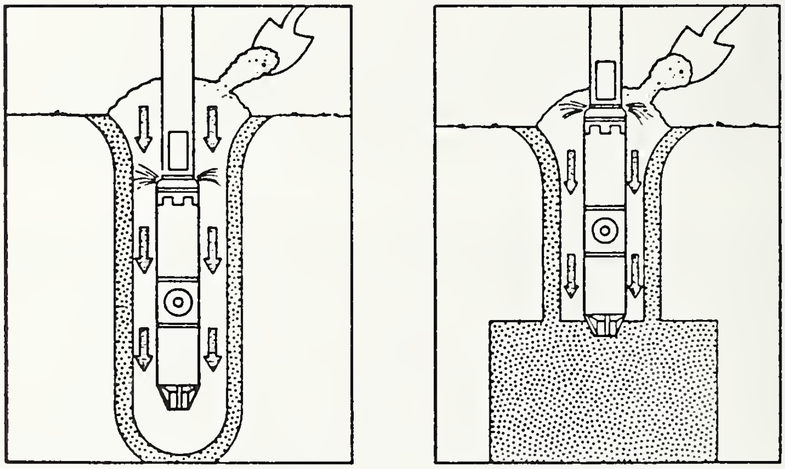
In general, vibroflotation can increase relative density by 20 to 40 percentage points. Allowable bearing pressures can be increased to 2 to 3 tsf [5-35]. Figure 5-15 illustrates typical patterns and spacings of vibroflot holes required to provide a density equivalent to 3 tsf bearing capacity on 3 to 11.5 ft square footings.

The following empirical rules for design of vibroflot hole spacing were determined from extensive full scale experimentation on granular soils [5-36].



1 Vibroflot is positioned over spot to be compacted and its lower jet is then opened full.

2 Water is pumped in faster than it can drain away into the subsoil. This creates a momentary "quick" condition beneath the jet which permits the Vibroflot to settle of its own weight and vibration.



3 Water is switched from the lower to the top jets and the pressure is reduced enough to allow water to be returned to the surface, eliminating any arching of backfill material and facilitating the continuous feed of backfill.

4 Compaction takes place during the one-foot-per-minute lifts which return the Vibroflot to the surface. First, the vibrator is allowed to operate at the bottom of the crater. As the sand particles densify, they assume their most compact form. By raising the vibrator step by step and simultaneously backfilling with sand, the entire depth of soil is compacted into a hard core.

FIGURE 5-13. TECHNIQUE OF VIBROFLOTATION [5-33]
SOURCE: VIBROFLOTATION
FLOTATION CO.

a. At distances greater than 3 ft from a single vibroflot, relative density does not increase above 70 percent.

b. The overlapping effect is small for spacings greater than 8 ft.

c. Relative densities greater than 70 percent can be achieved within a compacted area for spacings less than 6 ft.

d. The effect of adjacent compactions can be superimposed.

e. The same compaction results can be achieved by either square or triangular pattern spacings, but a triangular spacing is preferred because it gives the greatest compaction effort overlap.

D'Appolonia and others also present a design procedure for determining vibroflot spacing required to obtain a minimum relative density [5-36].

Some excellent case studies of the vibroflotation technique can be found in the literature [5-37, 5-38].

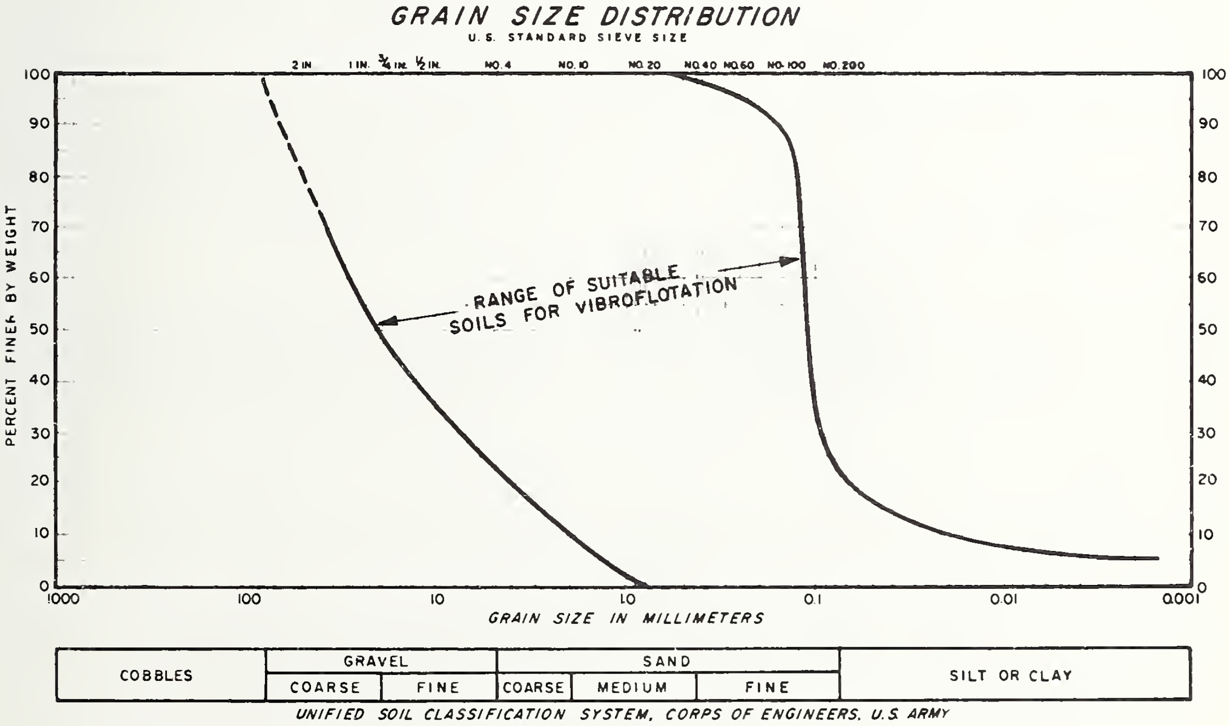
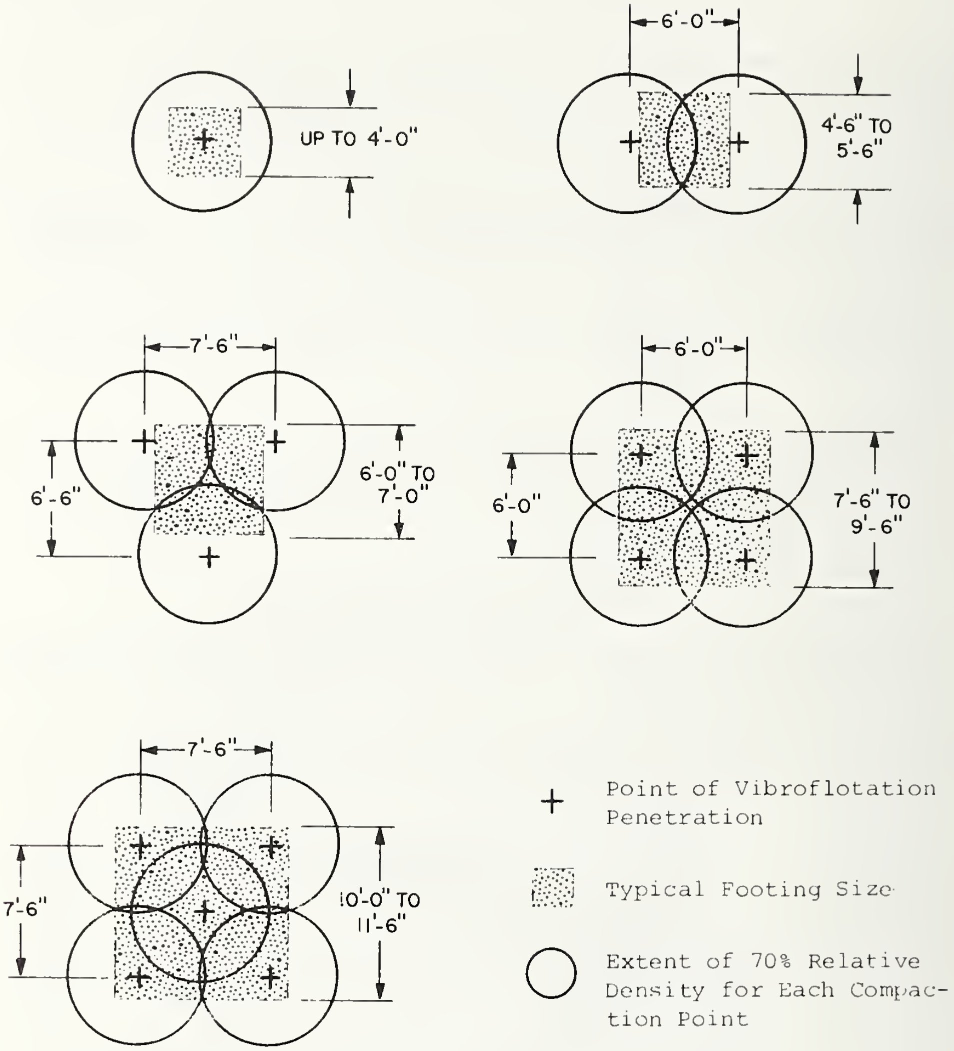


FIGURE 5-14. RANGE OF SUITABLE SOILS FOR VIBROFLOTATION [5-33]

SOURCE: VIBROLOTATION
FOUNDATION CO.



Note: Compaction Spacings are for an allowable bearing capacity of 6000 PSF.

FIGURE 5-15. TYPICAL VIBROFLOT SPACING [5-33]

SOURCE: VIBROFLOTATION FOUNDATION CO.

5.5.2.2 Blasting

Soils best suited for densifying by blasting are loose, saturated, cohesionless materials [5-39]. But recent studies of blasting have indicated its success for densifying sands above the ground water table [5-40]. Densification by this method has been reported to depths of 65 ft [5-35]. The blasting technique involves burying explosives which when fired cause liquefaction followed by expulsion of pore water and densification. The basic procedure is as follows:

a. Install a hollow pipe to the desired depth

b. Lower an explosive charge to bottom of pipe

c. Withdraw the pipe

d. Backfill the hole

e. Fire the charge(s) according to a pre-established pattern

The greatest amount of densification occurs immediately after the blast; the remaining densification occurs within a few minutes. The blasting technique is suitable for the same soils as vibroflotation, as shown in Figure 5-14. Other investigators have had success with silts [5-41]. Typically blasting can improve relative density by 15 to 30 percentage points, but it can seldom attain a maximum relative density of 80 percent [5-35].

The design of a firing pattern usually requires field tests. An empirical formula relates the weight of a charge (W) in lbs to a radius of sphere of influence (R) in ft as follows [5-35]:

$$W = CR^3, \text{ Note: } C = 0.0025 \text{ for charges with 25 percent dynamite}$$

Weights of the charges typically range from 1/2 to 8 lbs, and 3 to 5 blasts are fired in sequence. Figure 5-16 shows a typical firing pattern for densifying a loose, uniform, fine micaceous sand for support of a power transmission tower foundation [5-42].

There are no specific design steps. The following empirical rules are commonly used in determining blasting patterns [5-35]:

a. Repeated shots are more effective than a single large one or several small ones detonated simultaneously.

b. Each successive charge in a given area causes less densification than the one preceding.

c. Little densification occurs in the upper 3 ft of the layer. This zone requires surface compaction.

d. The center of the charge should be at a depth of about 2/3 the thickness of the stratum to be densified.

e. The horizontal spacing between blast holes varies from 10 ft to 25 ft and is governed by the depth of stratum to be densified and the desired overlapping effect of charges. For spacings less than 10 ft, adjacent charges may be prematurely set off.

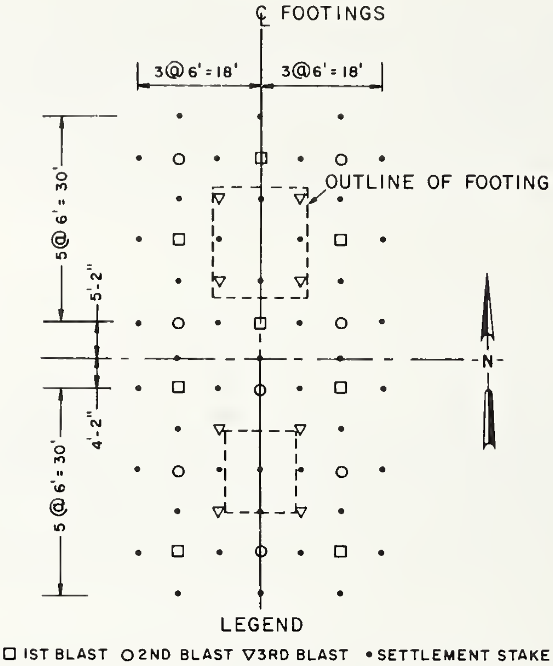


FIGURE 5-16. TYPICAL FIRING PATTERN FOR COMPACTION BY BLASTING [5-42]

SOURCE: PRUGH

5.5.2.3 Compaction Piles

The compaction pile is specifically employed to densify cohesionless soil strata. Typical depths of compaction range from 30 to 40 ft. Densification results from the displacement of soil equal to the volume of the pile and from the vibration effect of the pile installation.

Typically a casing with a detachable end plate is driven to the desired compaction depth; it is then withdrawn while the hole is simultaneously backfilled with sand. The efficiency of compaction piles is reduced for loose cohesionless deposits which are partially saturated.

Meyerhoff has investigated the amount of compaction by driving a straight sided displacement pile into a cohesionless soil [5-43]. The horizontal extent of the compacted zone, along the pile shaft, is approximately 5 pile radii with a slightly larger zone extending below the pile.

Design of compaction pile spacing is very empirical. Spacings are generally 3 to 5 ft apart. On the average, the increase in relative density over a particular site treated by compaction piles can be approximated from the total volume of driven piles and the amount of surface settlement [5-35].

Very few case histories describe the use of the compaction pile. Lehr [5-44] and Abaley and Askalanov [5-45] describe densifying loess deposits with compaction piles.

5.5.2.4 Grouting

The grouting technique involves pressure injection of a grout mix into the soil to cause densification. A variety of grout types exist today and use of each one depends largely on the soil type to be densified, as illustrated in Figure 5-17.

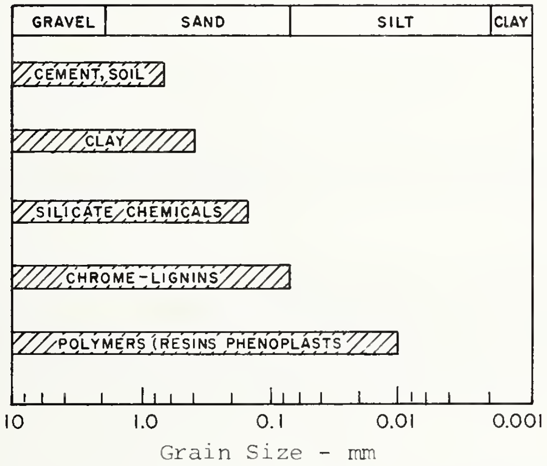


FIGURE 5-17. SUITABLE GROUT TYPES FOR VARIOUS SOIL TYPES [5-35]

SOURCE: MITCHELL; p. 86

Grouting is a relatively high cost soil improvement technique due primarily to the costs of materials, specialized techniques, and field control measures necessary for satisfactory implementation. Since sufficient confinement is required to obtain the needed injection pressures, grouting is generally limited to zones of relatively small volume. The technique is applicable for filling large voids to prevent excessive settlement or for increasing allowable soil pressures for support of structure loads. Table 5-12 summarizes the most common uses for grouting, many of which are applicable for improvement of landfill areas.

There are no established rules of design to be followed for developing a grout spacing pattern for a particular job. Experience usually dictates the design and method of application. Some typical grout patterns for water cut-off are presented in the literature [5-46].

TABLE 5-12. COMMON USES FOR GROUTING [5-35]

Prior to Construction

1. Control water problems during boring and sampling.
2. Fill voids to prevent excessive settlement.
3. Permit increases in allowable soil pressures relative to the untreated soil for both new structures and additions to existing structures.

During Construction

1. Control groundwater flow.
2. Prevent loose sand densification under adjacent structures due to pile driving.
3. Increase stability of granular soils beneath existing structures thus reducing lateral support requirements.

After Construction

1. Underpinning (compaction or displacement grouting, mudjacking).
2. Reduce machine foundation vibrations.
3. Eliminate seepage through cracks, joints, and pores.

SOURCE: MITCHELL; p. 85

Evaluation of the effectiveness of some grouts has indicated that soils having permeabilities greater than 5×10^{-4} cm/sec can be grouted [5-35]. A groutability ratio (if greater than 25) is commonly used to determine successful cement and clay grouting of soils:

$$\text{groutability ratio} = \frac{(D_{15})\ \text{soil}}{(D_{85})\ \text{grout}} > 25$$

Karol [5-47] has estimated the radial distance , r, in feet from a grout point to which a chemical grout may penetrate:

$$r = 0.62\ {}^{3}\frac{Rgt}{n}$$

where R = ratio of water to grout viscosity

g = rate of grout take (cu ft per min)

t = gel time (min)

n = soil porosity (dimensionless)

Several important characteristics of a good grout mix are listed below:

a. Stability and the possibility of segregation within soil and cement grouts

b. Setting time (It is important to get grout to the right place at the right time.)

c. Volume of set grout (A maximum volume with minimum weight of material is usually desired.)

d. Adequate strength to prevent washing out and to support imposed loads

e. Viscosity (generally the lower the better)

f. Rheological properties (yield stress, thixotropic properties, gelling characteristics)

g. Particle size and size distribution

h. Permanence

The following paragraphs briefly described the most commonly used grouts. Additional information can be found in an article by Leonards [5-27].

5.5.2.4.1 Soil and clay grouts. The soil and clay-water grouts are the least expensive, relative to material cost. Their use is primarily limited to injection in coarse-grained soils. Some disadvantages of these grouts are: (1) difficult to inject, (2)no cementing action, and (3) small permeability reduction.

A well-graded sand is commonly used in the soil-water grouts. Bentonite is commercially available for use in clay grouts. A clay-cement grout is also a common grout mix able to develop a mixture strength up to 1,000 psi, but these grouts do not have well defined setting times and develop their strength slowly.

5.5.2.4.2 Cement grouts. These grouts are mostly used to fill voids or joints in large in-situ rock masses; they have also been used to grout sands and gravels [5-48].

5.5.2.4.3 Chemical grouts. The chemical grouts consist of the silicate chemicals, chrome-lignins and polymers. These grouts have the most expensive material cost, but they have three attractive advantages: (1) absence of particulate material, (2) low viscosity, and (3) control of setting time.

Chemical grouts can be classified as 'one shot' and 'two shot'. One shot grouting requires premixing all ingredients before injecting them into the ground. A chemical reaction takes place after the grout is in place, at which point the grout converts to a solid or gelatinous mass. A two shot grout involves injecting one chemical into the ground followed by a second. As the chemicals make contact, a reaction between the two results in the formation of a precipitate in the pore spaces. AM-9 is a commonly used one shot grout. A common two shot grout consists of an injection of a sodium silicate followed by an injection of a calcium chloride. This combination results in a silicate get information.

The two shot grouts usually result in higher strengths, but they are generally slower to react and require closer spaced grout holes and higher injection pressures. Often no guarantee can be set for complete interpretation between the grouts.

5.5.3 Improvement Methods Applicable to Silt and Clay Muck

5.5.3.1 Stone Column

As described previously, vibroflotation is a technique commonly used for densifying sands and gravels. Approximately 15 years ago a variation of the vibroflotation technique, which permits strengthening of clay materials, was introduced in Germany. This technique is called the "vibro-replacement" or "stone column method."

The stone column method involves construction of a vertical hole in the clay with a vibroflot and partially backfilling with a coarse granular backfill. The backfill material usually consists of coarse gravel, crushed stone, or slag with a particle size between 3/4 and 3 in. The vibroflot is then lowered back into the hole to compact the backfill material by vibration. Repetition of the process results in the production of a very dense coarse granular 'stone' column within the clay material.

The lateral movement of the backfill material depends largely on the consistency of the in-situ clay material. The softer grounds yield the largest column diameter. Typically, the densified column of stone is 2-1/2 to 3-1/2 ft in diameter. Design generally calls for a triangular pattern of stone columns spaced from 5 to 9 ft apart. A 2 to 3 ft thick compacted granular fill blanket is usually placed over the stone columns to help distribute the foundation loads to the underlying soil. Hughes and Withers have prepared a review of empirical design procedures [5-49].

The stone column concept of load transfer can be described as follows. Initially, the stone column acts as a pile. As the foundation load is increased, the piles displace laterally which activates a passive condition to the weaker clay materials. Simultaneously, the stone column acts as a drain to remove excess pore water from the consolidating clay mass which becomes stronger. This cycle of operation continues until an equilibrium point is reached and the entire foundation area is mobilized to a uniform bearing pressure. This method has been successfully used to allow shallow footings to be used in areas that would otherwise require more expensive deep foundations or mats. A number of case studies have been documented which describe the use of the stone column method [5-32, 5-50].

Field experience has shown that a 3 ft diameter stone column installed in a medium stiff to soft clay can be designed to support a load of 20 to 30 tons per stone column [5-32]. Higher bearing capacities can be reached in stiffer soils.

5.5.3.2 Electro-Osmosis

Electro-osmosis is a method for improving fine-grained soils such as clay and silts. Most applications have been for dewatering and consolidation. The method was discovered by Reuss in 1809.

The purpose of electro-osmosis is to induce water movement by applying a direct electrical current supplied by an anode and cathode embedded into the soil. In very simplified terms, the phenomenon of electro-osmosis relates to the double electric layer (or double diffuse layer) at the surface of clay particles. The outer layer is positively charged and the inner layer is negatively charged. When an electric field is induced, the positive ions in the outer layer move toward the cathode, carrying associated water molecules with them. The overall result is a general flow of water towards the cathode.

Many of the theories developed for electro-osmotic water flow in capillaries have been applied to estimates of electro-osmotic flow rates in soils. All of the theories vary slightly depending upon the particular assumptions made. In 1952, Leo Casagrande presented a simplified formula which is similar to the formula used to measure the hydraulic flow in a capillary tube. Assuming flow in soils to be through a bundle of capillaries, Casagrande formulated the total flow, Q, to be [5-51]:

$$Q = k_e i_e A$$

where $k_e = \frac{\varepsilon \ \xi}{4\pi n} \frac{e}{1+e}$

k_e = coefficient of electro-osmotic permeability

ε = dialectic coefficient

ξ = beta potential

n = viscosity

e = void ratio

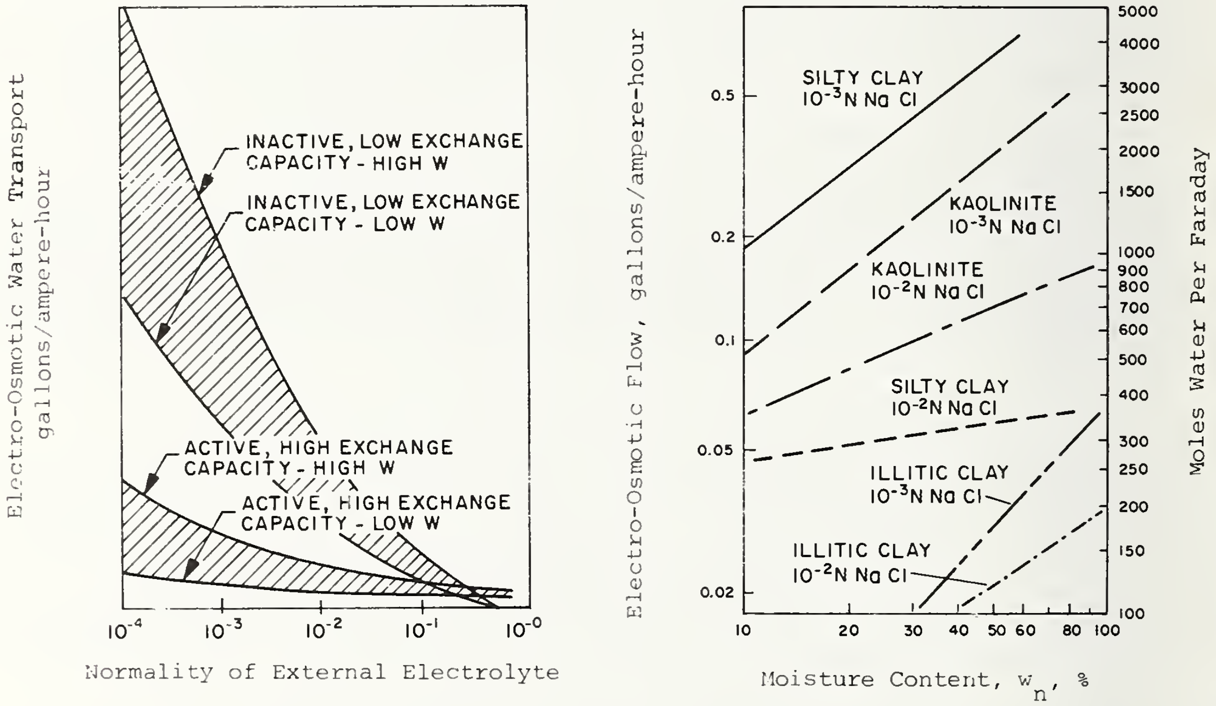
i_e = electrical potential gradient

A = cross sectional area of flow

Casagrande's formulation is based on the assumption that the thickness of the diffuse double layer is small compared with the size of the pores.

The coefficient of electro-osmotic permeability has been found to vary by only one order of magnitude for all soils with an average value of 5 x 10^{-5} square cm per second-volt (or cm/s under a 1 volt per cm potential gradient). However, the relation between the amount of water discharged by osmosis and the quantity of electricity consumed (usually measured in gallons per hour per amp) is not simple. This quantity depends on water content, exchange capacity, and free electrolyte content of the soil. Figure 5-18 illustrates graphically some relationships for predicting electro-osmotic flow for various clays.

The principles of electro-osmotic flow have been applied to soil engineering problems related to the theory of consolidation, pile driving, dewatering, and moisture proofing [5-35]. Casagrande [5-53] prepared an extensive state-of-the-art review of electrical stabilization.



(a)

Schematic Prediction of Electro-Osmosis in Various Clays According to the Donnan Concept

(b)

Electro-Osmotic Flow Versus Water Content in Clay-Water-Electrolyte Systems

FIGURE 5-18. DESIGN CHARTS FOR PREDICTION OF ELECTRO-OSMOTIC FLOW [5-52]

SOURCE: GRAY & MITCHELL; pp. 217, 229

Bjerrum and others [5-54] present an excellent case study whereby the strength of a quick clay was increased utilizing electro-osmosis. The clay strength was more than doubled, from 0.9 to 2.0 tsm to a depth of 10 m over an area measuring 10 m by 20 m. The direct cost for improvement amounted to $1.20 per cubic meter (cu m).

5.5.3.3 Vertical Drains

Vertical drains such as vertical sand drains, paper drains, and plastic wicks may be used in conjunction with surcharging to accelerate the rate of settlement of soft, saturated soils. Drainage techniques would normally be applied only when the muck of underlying natural soil deposits are saturated so that removal of excess water (or water pressure) will significantly improve the strength and settlement characteristics of the soil.

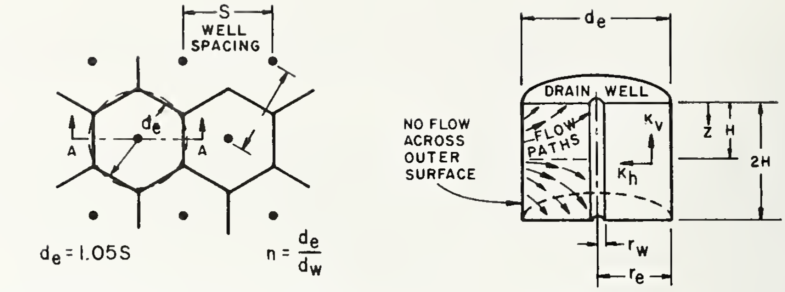
As mentioned previously, sand drains are an effective method for increasing the rate of consolidation of saturated deep clay or silt layers. The sand drain acts as a vertical internal drainage channel for the dissipation of excess pore water. Design is based on the theory of radial and vertical pore water flow developed by Barron [5-55] and Terzaghi. Figure 5-19 illustrates these basic theories. In design, the vertical and horizontal water flows are considered separately. Typically, sand drains are 18 to 20 in. in diameter and are spaced 6 to 10 ft apart in a triangular pattern [5-27]. The complete installation consists of installing a vertical column of sand (i.e., the drain), placing a top sand blanket over the soil stratum, and placing the surcharge load on the sand blanket. The blanket serves as an additional drainage path for water.

Some of the methods used today for installation of sand drains are rotary drill, mandrel (closed, open, driven, or jetted), continuous auger (solid or hollow stem), and vibratory driving. The most common method is the driven closed-end mandrel. The installation procedures result in a certain degree of disturbance to the treated soil adjacent to the sand drain. This zone of disturbance is called the 'smear' zone. It is important in the final analysis of the installation process to assess the potential severity of the smear zone. Table 5-13 summarizes some of the disturbance effects caused by sand drain installation.

A recently published article on the state of the art of sand drains describes both design and installation techniques [5-56]. The article also presents five case studies of sand drain installations.

Variations of the sand drain concept have been developed around the world.

Japanese engineers have developed a sand wick which is basically a thin synthetic plastic sheet, very flexible but sturdy, with continuous vertical channels or slots. These slots effectively act as drainage paths for water to dissipate by capillary action. These devices have been used extensively in Japan for increasing the rate of consolidation of clay and silt tunnel muck in conjunction with surcharging.



a. PLAN OF DRAIN WELL PATTERN

b. SECTION A-A

Vertical Consolidation:

$$C_{v-v} = \frac{k_v(1 + e_0)}{a_{v-v}\,\gamma_w} = \frac{H^2 T_v}{t}; \quad \text{OR} \quad t = \frac{T_v H^2}{C_{v-v}}$$

Radial Consolidation:

$$C_{v-h} = \frac{k_h(1 + e_0)}{a_{v-v}\,\gamma_w} = \frac{d_e^2 T_h}{t}; \quad \text{OR} \quad t = \frac{T_h d_e^2}{C_{v-h}}$$

Combined Radial and Vertical Flow:

At any time:

Excess Pore Water Pressure Ratios

$$\left(\frac{u}{u_o}\right)_{v+h} = \left(\frac{u}{u_o}\right)_v \times \left(\frac{u}{u_o}\right)_h$$

At A Point

$$\left(\frac{\bar{u}}{u_o}\right)_{v+h} = \left(\frac{\bar{u}}{u_o}\right)_v \times \left(\frac{\bar{u}}{u_o}\right)_r$$

Average Values

Degree of Consolidation

$$U = 1 - \frac{u}{u_o}$$

At A Point

$$U = 1 - \frac{\bar{u}}{u_o}$$

Average Value

FIGURE 5-19. THEORY OF RADIAL AND VERTICAL PORE WATER FLOW FOR SAND DRAIN DESIGN [5-56]

SOURCE: JOHNSON; p. 151

The sand wicks are installed using a special mandrel to push them to the desired depth. Sheet lengths can be easily cut in the field. Interviews with Japanese engineers and contractors claim this device is more economical than the conventional sand drain used in the United States.

TABLE 5-13. DISTURBANCE EFFECTS RESULTING FROM SAND DRAIN INSTALLATION [5-35]

SOURCE: JOHNSON; p. 156

Disturbance Effect	Remarks
Smear	Can be caused by any method of installation, even by a thin sharp knife drawn through soft clay
Soil displacement and remolding effects	Outward soil displacement caused by driven closed-end mandrels Inward soil displacement resulting from jetting methods or withdrawal of solid-stem augers Either outward or inward soil displacement may result from hollow-stem auger methods, depending on rotation and advance rates of auger
Grouting of thin sand layers	Caused by natural drilling mud formed by jetting methods
Thin film of mud on sides of drain	Caused by natural drilling mud formed by jetting methods
Contamination of sand backfill in drain	Possible in jetting methods if washing during jetting is insufficient. Also possible when withdrawing driven mandrel if sand sticks in mandrel
Distortion of thin sand layers	Most likely with driven mandrel method, possible with solid- or hollow-stem augers. May be severe in varved or thinly bedded deposits

The sand wick concept has been developed in the United States. Healy & Long [5-57] report the development of a prefabricated fin designed to increase the rate of soil drainage. The method was originally developed for draining embankment slopes to prevent stability and erosion problems. Use of this drainage system can eliminate the need for expensive select backfill or filter material otherwise specified to obtain a free draining slope area. The drains can be economically installed during construction.

The prefabricated fin underdrain is illustrated in Figure 5-20. The drain consists of a plastic pipe with a slot cut down its entire length and a vertical channel fin fitted into the slot. The fin, which typically consists of an expanded aluminum sheet or polyvinyl tube fencing, is surrounded by a filter cloth material designed to prevent soil particles from migrating into the fin. The vertical fin acts to intercept water moving horizontally and rapidly conducts it to the bottom drain pipe where the water can be removed from the area.

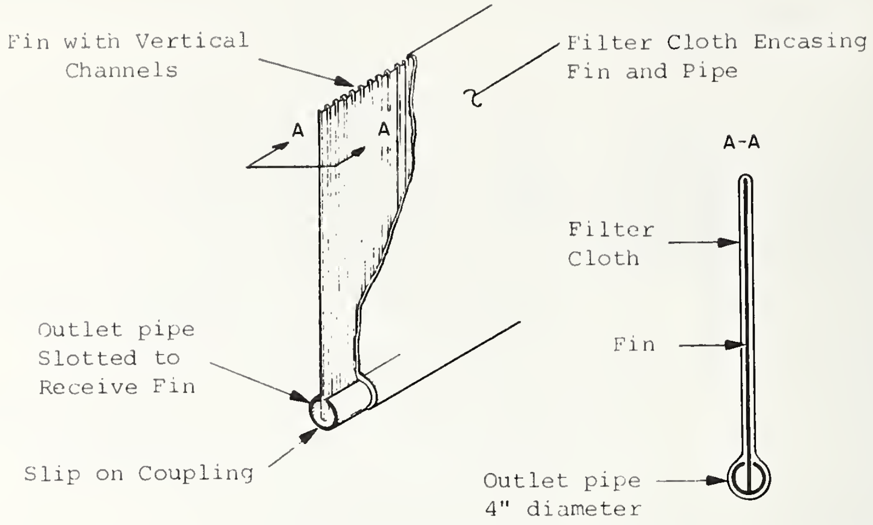

Fin with Vertical Channels
Filter Cloth Encasing Fin and Pipe
A
A
A-A
Filter Cloth
Fin
Outlet pipe Slotted to Receive Fin
Slip on Coupling
Outlet pipe 4" diameter

FIGURE 5-20. PREFABRICATED FIN UNDERDRAIN [5-57]
SOURCE: HEALY & LONG

5.5.3.4 Thermal Treatment

Heating or cooling a fine-grained soil can change its physical properties. These improvement techniques are usually complex in execution, and therefore very high costs are associated with thermal treatment.

Thermal heating of a fine-grained soil to temperatures between 100° and 1000°C can decrease water sensitivity and swelling compressibility and increase strength. The use of thermal treatment has been confined almost exclusively to Eastern European countries and Russia [5-35]. It has been successful in the following applications:

a. Stabilize weak clay soils and loess

b. Improve soil prior to construction

c. Stabilize potential landslide areas

Three basic techniques have been used: (1) burning liquid or gas fuels in burners lowered into a borehole, (2) injecting hot air under pressure through pipes and boreholes, and (3) burning liquid or gas fuels under pressure in sealed boreholes. To date, the third method has produced the best results. Litvinou [5-58] describes a case study for treating clayey soils in which a consolidated zone of 1.5 to 2.5 m in diameter by 8 to 10 m deep was formed with one 15 to 20 cm diameter borehole. The period of treatment was 8 to 10 days.

Thermal treatment has not been used in the United States because of lack of knowledge and experience.

Ground freezing, however, has been used in the United States for temporary treatment of fine-grained soil masses. Complete freezing of the pore water in the soil is most common, but a slight cooling has been used to establish a thermal gradient capable of causing the movement of pore water.

6. CONTINGENCY ASSESSMENT

6.1 INTRODUCTION

Because of the inherent unpredictable nature of subsurface conditions, underground work involves more contingencies or risks than surface construction. Thus tunneling contractors are familiar with calculated risks but are not anxious to increase their exposure to risk. This point was emphasized at a conference sponsored by the National Science Foundation where it was concluded that risks and incentives, control the introduction of new technology to underground construction more than technological feasibility [6-1]. Introduction of muck utilization, either as a new concept or as a new contractual condition, must be accomplished without imposing undue risks or hardships.

It was found that individual, corporate, and institutional entities involved in the planning, design, building, funding, and operation of underground facilities have different roles and financial interests in the project. Thus a technological benefit to one member may be of little concern to the other organizations. The technical, contractural or other revisions to the standard operational procedure should appeal to more than one member of the team. Also in order to minimize the impact of the new provisions, the change should be implemented in small steps with the emphasis on obtaining useful results in a short period of time [6-2]. Muck utilization satisfies the criteria for ready adaptability and benefit to the owner, contractor, and city agencies involved in urban transit projects.

Thorough planning is required, however, in order to properly assess the value of muck utilization and the potential difficulties which may develop. Murphy's Law, "If something can go wrong, it will," applies to tunneling. The hazards associated with a particular tunneling project must be evaluated well in advance so that alternative construction plans can be immediately activated. Thorough planning and flexibility are the key requirements for successful muck utilization.

The following sections outline some of the contingencies which might develop during a tunneling project. Recommended planning actions are also provided.

6.2 SUBSURFACE CONDITIONS

6.2.1 Subsurface Investigations

A well planned and executed subsurface investigation program can be an invaluable asset to the owner, engineer, and contractor. The program is prepared to provide the necessary information required to design and build the structure. Soil, rock, and groundwater conditions are evaluated including the geological and engineering properties of the materials. This same information is vital to the planning of a muck utilization program.

In the BART project, for instance, test pits and two 5 x 7 ft test drifts averaging 1200 ft in length were completed to obtain samples of the in-situ soil and to evaluate the anticipated hard ground conditions in the Berkeley hills [6-3]. These explorations would have provided an ideal opportunity to obtain material samples to evaluate muck properties. Similar test pit and test drift explorations were conducted for the Washington METRO [2-12, 2-14 and 6-4]. The test pit provided information on in-situ soil stratification (and a chance to obtain bulk samples) while the drifts increased the knowledge of rock conditions in the Dupont Station area. A complete subsurface program conducted for the 16 ft diameter tunnel from the Wilson Avenue to the Central Water Filtration Plant in Chicago resulted in locating the tunnel in a deep rock strata which did not have the rock problems encountered in other rock tunnels [6-5]. The merits of a well planned subsurface program cannot be overemphasized.

6.2.2 Changed Conditions

The phrase "changed conditions" raises the spectre of extra payments and construction problems to owners and contractors, respectively. Often the problems are real but they do not always involve major changes in soil, rock, or groundwater conditions. Rather the changes may be subtle such as a variation in the jointing pattern in a rock mass or the existence of boulders larger than any indicated in the test explorations. A short anecdote may best explain the reasons for these changes. While accompanying the noted engineering geologist, Dr. C. P. Berkey, on an inspection of a dam site, the engineer continually quizzed the expert on the likely subsurface conditions. Finally Dr. Berkey replied, "Young man, I can't see one inch further into that hill than you can!" [6-6]. During the exploration stage, only a finite number of samples can be obtained. Additional costs and the law of diminishing returns prevent sampling every foot of the way along a tunnel route.

Descriptions of changed conditions usually fall into one of the following categories: (1) unforeseeable, (2) foreseeable, (3) preventable, and (4) mistaken [6-7].

Unforeseeable conditions are problems which are truly unknown to the owner, engineer, or contractor until they are uncovered in the excavation. The remaining categories may be attributed to lack of knowledge, lack of experience, or ignorance on the behalf of all parties to the problem. The unforeseeable conditions can be subdivided into conditions (1) where actual conditions are substantially different from those described in the bid documents and (2) where very unusual geologic conditions developed unexpectedly. The owner normally absorbs the extra costs associated with a verified changed condition. The costly changed condition problems, however, appear to be related to problems of tunnel support and may not have a major effect on muck properties.

For example, an unexpected joint several inches thick and filled with crushed rock and clay was encountered in the rock wall between the surge chamber and powerhouse in the Churchill Falls Project [6-8]. The joint, unidentifiable in the rock cores, endangered the stability of the wall. Extra length rock bolts were installed to remedy the situation. This joint, however, would have a negligible effect on the properties of the muck removed from both the powerhouse and surge chambers.

While excavating the METRO twin tunnels crossing the Potomac, the contractor decided that steel ribs and lagging were better suited to the rock than the planned shotcrete and rock bolt method of support. Overbreak was a definite problem and as a result WMATA agreed with the change in support systems. The overbreak was attributed to the combination of the arrangement of the rock strata and the method of blasting [6-4]. Thus the type of rock muck would not have been affected by the changed conditions.

Excavation of the Richmond Water Tunnel in New York City was initially scheduled for a hard rock TBM. The machine made excellent progress for the first 75 ft but then progress slowed down until the contractor elected to finish the work by conventional drill and blast methods. Although the rock conditions did not change, the change in construction methods significantly altered the properties of the rock muck.

In order to minimize the problem of changed conditions, it is recommended that a thorough subsurface investigation be completed and that all data and interpretations be provided to the contractor with the bid documents.

6.3 METHOD OF CONSTRUCTION

6.3.1 Selection of Excavation Method

Generally, the owner should accept the method of excavation suggested by the contractor [6-9]. The selection of the method is based on geologic conditions, available equipment, anticipated rate of progress, and other factors which influence the project completion time. In soft ground tunneling, the conventional methods of excavation will have little effect on the muck gradation or properties. In rock tunneling, the obvious alternatives are drill and blast versus TBM which produce significantly different gradations of muck. In some instances minor changes in the final method of excavation might be beneficial. For instance, if drill and blast patterns are adjusted to produce a smaller rock muck, the cost for additional rock drilling equipment, drilling time, and explosive could be insignificant in the total project shedule. But to limit the contractor to a TBM just to produce crushed rock could be very expensive, particularly on a short tunnel. Therefore, the muck utilization program should be based on the likely method of construction but should be flexible and adaptable to a range of excavation methods.

6.3.2 Effects of Changed Conditions

Based on the previous discussion of changed conditions, it is unlikely that major changes in ground conditions will necessitate a switch from soft ground to hard ground mining techniques or vice-versa. Mining through a major fault zone requires a change in technique which results in a change in muck quality . A thorough subsurface exploration program identifies these zones and prepares the muck utilization program for the change in mining methods and muck properties.

Changes in groundwater conditions may result in major changes in muck quality. Options available to the contractor include compressed air, dewatering, freezing, and grouting. The first three methods do not affect the physical properties of the muck; the last method adds grout to the muck product. If at the start of a project the dewatering requirements are uncertain, then the owner may require that a compressed air plant be moblized and used only when necessary. Since compressed air tunneling is expensive, grouting may be used in a localized area of the tunnel. Methods must be chosen on the basis of a cost comparison of the alternatives and a possible change in muck quality.

The sewer interceptor along Manhattan's West Side was constructed using chemical grout to stabilize soil below the water table [3-35]. The other alternatives, compressed air, freezing, and dewatering, were ruled out by cost, utility obstructions, and specifications (settlement from dewatering), respectively. Thus grouting was the only alternative.

If grouting is a likely choice, and if grouting might affect the quality of the muck, then a test program should be completed to evaluate the properties of the grouted soil or rock.

6.4 DELAYS IN THE CONSTRUCTION PROGRAM

6.4.1 Funding

Coordination of muck utilization programs can be halted immediately if no funds are available for either the tunnel or for the related utilization program. Also the timing of construction activities must be considered. Major construction activities require Federal assistance. The Washington METRO, for example, accelerated the completion of design for its first cut and cover project. The design and contract documents were completed in 10 months, in time for the anticipated release of funds. The funding, however, was held up for an additional 14 months [6-4].

Similar concern about funding schedules was encountered during interviews in Chicago with representatives of the Department of Public Works. The muck planning efforts for the Deep Tunnel Project involved simultaneous activities in (1) the deep tunnel, (2) the subway extension, and (3) reactivation of the harbor dredging program. Lack of simultaneous funding from different Federal sources would decrease the effectiveness of the muck planning project. However, since no one at the local level can guarantee the actions of the Federal agencies, the planning must account for potential problems .

Planning, design, and initial construction of Atlanta's MARTA system are underway. At one phase of the funding from Federal sources, MARTA was granted only $80 million of the $237 million requested. Atlanta is committed to the system and thus is planning to continue construction but with an extended completion time and with more local funding [6-10]. The scheduling of the entire project is thus affected by factors which are not under local control. Adjustments simply have to be made.

6.4.2 Legal or Environmental Problems

Construction activities in urban areas can create unacceptable levels of noise. City codes and OSHA requirements must be satisfied or residents can rightfully complain, and cause the job, including muck production and hauling to be stopped [6-11].

Environmentalists' concern for proper disposal of construction debris is apparent in the EIS statements which have been prepared for Atlanta and Baltimore [10-5, 10-10]. General plans for the disposal of materials were established in each case with an accounting of the total volume of material to be produced compared to the available disposal sites. The filling of wetlands can be opposed and thus the traditional dumping methods used by contractors can no longer be applied.

In another subtle case, a suit was brought against the Washington WMATA, claiming that the subway vibrations would be unacceptable to residential neighbors. The construction of that particular stretch of rock tunnel was deleted from the contract. The low bidder elected to use drill and blast methods rather than a TBM because costs for TBM mobilization would be too high to justify its use for the shortened route. This last minute litigation was probably the cause of a change from TBM muck to drill and blast muck. The muck utilization program must be flexible enough to absorb these changes.

6.4.3 Normal Delays

Strikes, weather, utility relocations, equipment breakdowns, and subcontractors' activities cause delays for a tunnel contractor. It is impossible to predict the nature or extent of these delays, but it is prudent to assume that something will delay the job for periods of a few days to several weeks. A survey of architects, engineers, and general contractors was completed to determine the delay factors which are most important or severe [6-12]. The respondents were asked to rate 16 typical problems affecting construction progress. The 6 most severe factors for each group are listed in Table 6-1 in order of their relative severity. Weather, labor, and subcontractors were the top three choices for each group; foundation conditions (changed soil or rock conditions) ranked sixth. The muck utilization program must be flexible enough to survive the inevitable delays caused by these factors.

TABLE 6-1. DELAY FACTORS AFFECTING CONSTRUCTION PROGRESS [6-12]

SOURCE: BALDWIN

Contractor Responses	Architect Responses	Engineer Responses
1. Weather	1. Subcontractors	1. Weather
2. Labor Supply	2. Labor	2. Subcontractors
3. Subcontractors	3. Weather	3. Labor
4. Design Changes	4. Manufactured Items	4. Manufactured Items
5. Shop Drawings	5. Finances	5. Finances
6. Foundation Conditions	6. Material Shortages	6. Foundation Conditions

Note: Responses listed in order of importance.

6.5 SATISFYING UTILIZATION SPECIFICATIONS

6.5.1 Criteria

The specifications for muck utilization programs must clearly establish acceptable limits for the quality of the muck to be supplied. These specifications can be prepared by the prospective commercial user or by an engineer or consultant retained to analyze the muck qualities and prospective uses.

A commercial industry, such as a brick manufacturing plant, cannot tolerate wide variances in the quality of the raw clay. Thus a ready set of specifications used by brickmaking plants can be used to evaluate the acceptability of clay muck as a raw material.

The criteria for accepting raw materials may differ among sand and gravel plants, concrete ready-mix plants, and asphalt concrete plants. Local criteria may vary depending on the available aggregates and gradation specifications.

The requirements governing materials and placement methods for controlled landfills must be established based on engineering evaluation of the intended use of the fill. Thus gradation compaction requirements and allowable water content are factors which will affect the acceptability of muck.

6.5.2 Samples

Prospective users should be provided with samples of the anticipated soil or rock materials. These samples should be obtained during the subsurface investigation program in order to allow time for product evaluation. Basic geologic data can also be provided to indicate the extent of the soil or rock deposit which will be mined and to alert prospective users to the potential changes in material properties.

The geological data and the samples can provide additional means to confirm the suitability of muck for the potential use and thereby reduce the risk that the material will not meet the specified tolerances. In Washington DC for instance, a cutterwheel shield produced chips of stiff clay which were acceptable for brickmaking. However, when the machine encountered sandy deposits, the clay was no longer suitable for brickmaking and another disposal scheme had to be adopted. If the soil profile and typical samples had been evaluated beforehand, then the change in conditions would not have required a sudden change in disposal plans.

Materials handling systems such as conveyors, muck cars, and loaders do not adversely affect muck properties. Once the muck is produced at the face, the mechanical handling will not alter the physical characteristics. Thus the handling system to be used does not need to be considered when evaluating the results of tests on samples.

6.5.3 Debris

Construction debris can contaminate the muck and render it unacceptable. Care on the part of the contractor can prevent most severe debris problems. Some debris connot be removed from the muck once it has been introduced. For example, shotcrete methods will result in surplus concrete being mixed with the muck. The basic constituents of aggregate, sand, and cement may not affect the use of the muck in a landfill, but the debris can affect aggregate production or acceptability. The volume of normal debris is usually a very small percentage of the total volume, so minimal attention should prevent severe problems from developing.

6.6 CONTINGENCY PLANNING FOR MUCK UTILIZATION

The key factors controlling or minimizing contingency problems are (1) thorough planning and (2) flexibility.

6.6.1 Planning Efforts

Environmental and economic factors influence planning activities from the start of a project. Some of the concerns expressed by environmentalists include (1) minimum energy consumption during and after construction, (2) proper storage and/or disposal of excavated material, (3) minimum environmental disruption and, (4) a finished product that meets community and environmental goals [6-13]. Proper muck utilization planning will satisfy the environmentalist's demands under items 2 and 4 and thereby prevent last minute project delays caused by objection to random dumping or disposal processes.

Geologic analyses are often required in the preliminary stages of project planning in order to evaluate the overall project feasibility [6-14]. The same geologic analysis can be used for preliminary muck utilization planning. Typical preliminary data may only indicate general soil or rock profiles, approximate level of groundwater table, and an estimate of tunneling difficulties. Nevertheless if the concept of muck utilization is introduced in the early planning stages, then it will become an integral part of the project and will not have to be tackled in the end. By providing time for planning, the economic value of the muck can be determined, whether it is used for land reclamation or as a raw material for aggregate or another specilized use. Several tunneling projects completed in New York City illustrate the benefits of total materials handling and muck utilization planning [6-15].

The contract documents for the Richmond Water Tunnel provided that the contractor could at his option dump the rock muck to join two islands in the lower New York bay. A rock dike system would be constructed on each side and used to contain solid waste generated by the New York City sanitation department. The project was abandoned, however, because the blast rock particles produced during mining operations were too small for use as riprap. Thus, although the planning effort was in force from the beginning of the project and the bid documents provided for muck utilization, the project collapsed due to a last minute contingency problem. Since no alternative utilization plans had been prepared, the contractor disposed of the muck in other landfill projects and as riprap in other areas of the bay.

The construction of the East 63rd Street sunken tube tunnel from Manhattan to Queens is an example of a successful muck utilization plan. In a planned operation, muck was delivered to a landfill on the southern end of F. D. Roosevelt Island. Riprap was placed to stabilize the exposed slopes. Also the Manhattan end of the tunnel was excavated after the tubes had been placed, allowing muck to be hauled through the tubes and then to the fill site. This planning reduced traffic disruption from trucking operations and in the end was a net benefit to the contractor and the city.

The planning effort must be thorough, it must be initiated during the project feasibility studies, and it must be flexible, providing at least two methods of utilization or disposal.

6.6.2 Flexible Utilization Plans

At least two options for muck utilization should be evaluated during the planning stages. The options should consider uses appropriate for good quality muck and poor quality muck. If neither of the utilization plans are feasible, then outright disposal can be implemented. For example, muck can be incorporated into a variety of landfill projects ranging from high quality engineered, compacted fill to sanitary landfill cover or quarry backfilling. Then as the muck quality varies due to anticipated or unforeseen changes in ground conditions, the material can be sent to the appropriate fill site.

The timing or rate of muck production varies during the job. Therefore, customers for muck must be alerted to the possible delay in the day to day variations. Overall planning may indicate that an average of 1000 cu yd per day of muck will be produced, but the daily delivery rate may vary from 0 to 2000 cu yd. The contractor may find it more convenient, therefore, to stockpile material at the access shaft location. Compation equipment used at the fill site may not be 100 percent efficient, and muck may have to be stockpiled somewhere.

Stockpiling of muck is one method to provide additional time or "float" in the delivery schedule. Rock muck could provide a long-term source of aggregate for extension of surface rail lines (track ballast) or extension of parking facilities (bituminous concrete aggregate). By stockpiling the rock on a marginal land site, any soft compressible soils could be surcharged. Surcharging would develop surface settlements, creating a stable site for eventual development. The rate of delivery of materials to a stockpile site would be inconsequential, thus eliminating contingencies based on rate of advance problems. An appropriate storage site is required and should be located during the early planning stages to insure that lengthy land acquisition problems do not hinder the utilization scheme.

6.6.3 Contract Documents

The contract documents must clearly establish the contractor's role and responsibility in the muck utilization process. Location of the disposal area, prescribed trucking routes, method of placement, the sorting of debris, and other pertinent information or requirements must be provided in order to prevent confusion during the bidding period. A unit pricing schedule should be established to fix the costs for hauling muck to different sites in accordance with the alternative muck utilization schemes, including outright disposal by the contractor. The method of measurement of quantities should also be established, whether it be volume measured in place in the tunnel, truck volume, weight measure, or volume measured in place at the disposal site. The owner's representative would therefore be responsible for evaluating the muck on a daily basis and then implementing one of the utilization schemes. By providing several choices in the documents, the owner retains the flexibility needed to match the variations, foreseen or otherwise, which can develop in underground construction.

7. MUCK UTILIZATION RATIONALE

7.1 INTRODUCTION

Utilization of tunnel muck provides advantages to the owner, the contractor, and the public. The planning effort minimizes risks for the contractor, thus reducing bidding contingency allowances. The owner benefits from the increase in the value of land developed with muck or from other utilization schemes. The public benefits from the minimization or elimination of disposal practices which are detrimental to the environment. This section further discusses these benefits and proposes utilization guidelines.

7.2 ADVANTAGES TO OWNER

7.2.1 Competitive Bidding

The owner enables all contractors to bid on an equal basis by providing a conveniently located, easily accessible, site for disposal of tunnel muck; rather than giving special advantage to a particular contractor who may own or control a private landfill.

Since major tunneling projects often attract out-of-town contractors, the preplanned disposal program eliminates the practical problem of locating a disposal site in an unknown area. The owner thus attracts more bidders and reduces the number of contingency items carried by the contractor, thereby reducing anticipated costs.

7.2.2 Community Acceptance

Tunnel construction in urban areas always necessitates temporary inconvenience to the public. Problems often occur when contractors haul muck to a variety of locations selected without regard to community convenience. A well selected muck disposal area can reduce the number of trucks traveling through residential areas, spilling debris on streets or blocking traffic, and thereby minimize public discontent. Additionally, if it can be demonstrated that the muck is being used for the public benefit, for example, in the creation of a park, residents will be more likely to accept the annoyances caused by such a project.

7.2.3 Early Completion

A well selected disposal site enables the contractor to operate continuously by eliminating the possibility that he may have to shut down the tunneling operation while seeking a new disposal site or that dumping or hauling permits may be retracted.

7.2.4 Cost Savings

A definitive muck utilization or disposal plan reduces the contingency factors in the bid price for the cost of disposal. Lower bid prices represent a direct savings for the owner.

In addition, the owner benefits from the appreciation in value of marginal land which is improved by the placement of fill [7-1, 7-2]. Utilization of the muck as aggregate, backfill, track ballast or other usage in the transit construction reduces the volume of imported materials needed.

7.2.5 Revenue Increases

If vacant land, improved by filling with tunnel muck, is used to create commuter parking, industrial sites or housing within proximity of mass transit, the transit system benefits from the increased number of users with access to the system.

7.3 ADVANTAGES TO CONTRACTORS

7.3.1 Simplify Bidding Process

Contractors without access to a convenient disposal area cannot calculate costs accurately without having to consider where or at what cost they will dump this material. The muck utilization plan thus reduces an area of potential loss which could result from factors beyond the contractor's control.

7.3.2 Permits by Owner

With proper muck utilization planning, the owner arranges for the necessary trucking or land use permits. Often the time required for bureaucratic processing of permit applications or negotiations for land use can equal or exceed the bidding period. Although the contractor must abide by the permit regulations, he is relieved of the burden of obtaining these permits.

7.3.3 Maximum Utilization of Equipment

Since the location of the muck disposal site is known, the contractor can schedule his equipment to optimum advantage. For example, since site availability will not change from day to day, the trucking fleet can be in continual use.

7.3.4 Optimum Work Schedule

With assured access to a disposal site and with all necessary permits in hand, the contractor can drive the tunnel at the maximum rate, rather than adjusting the pace to match disposal efforts.

7.4 ADVANTAGES TO PUBLIC

7.4.1 Housing Opportunities

Landfills can be utilized to create areas for housing in urban areas. In many cases the high cost of suitable fill material prohibits land development. Tunnel muck provided at lower cost (possibly without charge) can make these housing developments economically possible.

7.4.2 Job Opportunities

Large employment centers can be created on landfills in urban areas.

7.4.3 Recreational Potential

Landfills used as parks or golf courses can fulfill needs in urban areas for additional leisure time facilities. Consideration of such use in conjunction with Green Acres programs is recommended.

7.4.4 Environmental Improvement

Geotechnically marginal tracts of land which have, by design or circumstance, become disposal areas for trash and garbage need no longer be eyesores or health hazards. Properly filled, these areas can be upgraded to become visually appealing.

7.4.5 Increase of Tax Base

Creating housing or industrial facilities on marginal lands can afford cities and states with substantial revenues from real estate property taxes, sales taxes, payroll taxes, etc. For example, a 100 acre landfill* could accomodate approximately 2 million sq ft of industrial buildings with an approximate value of $30 million. Taking a tax rate of 6 percent (which might be conservative for an urban area) property taxes might amount to $1.8 million annually. Computing employment at 500 sq ft per employee, the industrial buildings on the site could accommodate 4000 employees. If these workers were to be paid $200 per week (average), a total annual payroll in excess of $40 million is indicated.

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*For 1,600,000 cu yd of tunnel muck, 100 acres of land can be developed having an average fill height of 10 ft.

This same 100 acre area, if developed with housing of 16 units per area, $20,000 value per unit, would yield $1.9 million in real estate property tax revenues, based on a 6 percent tax rate.

7.5 UTILIZATION GUIDELINES

The following paragraphs recommend planning steps for developing technically suitable muck utilization plans. Muck utilization must be considered during the preliminary design phase so that recommendations relative to muck utilization can be incorporated into subsequent design decisions. For example, additional field or laboratory tests required for analysis of muck properties should be conducted as an extension of the normal subsurface exploration program. This "input" for the muck utilization program must be prepared at an early stage in the system design program.

The actual implementation of the utilization plan or plans will depend on an evaluation of the overall project schedule, municipal or state land use planning, and other factors which are discussed in Section 8 of this report.

7.5.1 Establish Route Alignment and Complete Preliminary Test Borings

The selection of the transit route alignment requires a comprehensive transportation study. Theories have been proposed that transportation follows land use and vice versa [7-3]. An assessment of land use and transportation corridors is beyond the scope of the planning for muck utilization. However, during the early stages of route analysis, muck utilization might "tip the balance" toward one of the alternate routes.

General knowledge of the geologic conditions in the area, supplemented by available test boring records (from other site investigations), could be used to establish preliminary subsurface conditions. Also, preliminary test borings should be completed to develop the generalized subsurface profiles along the proposed transit routes.

Preliminary route alignments and soil profiles which are prepared to aid in the evaluation of land aquisition and construction problems are also required in the preliminary analysis of muck properties.

7.5.2 Preliminary Muck Evaluation

Based on the preliminary design profiles, the general muck types can be assessed. Their general classifications relate to the basic categories of clay, sand and gravel, or rock-based muck. This information is then used to evaluate potential uses for the muck and to prepare recommendations which affect the proposed vertical and horizontal route alignment and the final subsurface exploration program.

7.5.2.1 Preliminary Potential Uses

From the preliminary subsurface profiles an estimate can be prepared for the quantities of clay, sand and gravel, or rock muck to be produced during construction. The potential uses for the muck can be evaluated by referring to the utilization chart (Table 5-1, p. 5-2) and from a knowledge of local uses of the same materials. These preliminary uses can then be used to prepare the recommendations affecting route alignment and the testing program.

7.5.2.2 Vertical and Horizontal Alignment

Preliminary horizontal and vertical alignments are established based on factors such as transportation requirements, land accessibility, zoning practice, and transit equipment requirements. Once the horizontal transit corridor has been established, it is unlikely that considerations of muck properties or value can justify a change in alignment. A change in vertical alignment, however, may be desirable for several reasons, including muck utilization. In order to avoid mixed face tunneling conditions, the tunnel could be lowered into rock or raised to undertake soft ground mining. Operating conditions, such as grades between stations, total depth of shafts, or station excavations, as well as construction problems and muck properties, are some of the factors to be considered. The value of the muck by itself is not sufficient to justify a change in alignment, but it may tip the balance in the decision making process.

7.5.2.3 Subsurface Exploration Program

Recommendations for additional samples or laboratory tests affect the subsurface exploration program for project design. The additional field and laboratory tests required for muck evaluation depend on the anticipated soil and rock conditions. Large volume samples are normally required as well as additional field and laboratory tests. The muck utilization tests should be completed in conjunction with the standard design program in order to minimize additional costs. It is important, therefore, that muck utilization plans be developed along with the preliminary system design plans.

Large volume samples are required in order to obtain representative samples for gradation analysis and to preserve a representative sample after destructive testing of a portion of the sample. These larger volume samples can be obtained from test pits or exploratory drifts or by increasing the volume of samples retained during the standard test boring program.

The completion of test pits or exploratory drifts may not be justified for muck utilization alone. However, in combination with other reasons, such as an evaluation of dewatering or mining problems, the test pits may be a reasonable approach. Test pits were completed for the Washington METRO and trial drifts were used for San Francisco's BART.

Larger volume samples can be obtained from the test boring program. The soil and rock sampling methods should require that all of the samples obtained from the field tests be saved for examinations. For example, the standard split spoon samples can recover a cylindrical soil sample up to 18 in. long. Normally a representative sample is saved in a glass jar, and the remaining 10 or 12 in. of soil are discarded. All of the samples recovered in the anticipated zone of tunnel or shaft construction should be retained for examination. This merely requires filling additional glass jars. The standard representative sampling can be used in other zones.

Some of the additional tests which may be required are listed below. A more complete discussion of testing procedures is presented in Section 4.

7.5.2.4 Clay Muck

The completion of field vane tests is recommended in order to assess the strength and sensitivity of the clay. When disturbed by construction activities, a highly sensitive clay can be remolded into a thick viscous liquid. An assessment of sensitivity is important for design, construction, and muck utilization purposes.

Laboratory consolidation tests should be completed on remolded samples in order to evaluate the compressibility of the clay after placement.

7.5.2.5 Sand and Gravel Muck

Large volume samples should be recovered in order to complete representative gradation analyses and compaction tests. Since test borings cannot recover particles larger than 2 or 3 in., test pits should be completed. Alternatively, large volume samples could be obtained when access shafts are excavated prior to the start of tunneling.

Laboratory tests include abrasion, soundness, and petrographic analysis required to evaluate the muck for use as aggregate. Also standard gradation and compaction tests should be completed in order to evaluate the suitability of the material for backfill in landfill projects or as fill materials for the transit property.

7.5.2.6 Rock Muck

Standard rock core samples should be obtained and representative core samples provided for destructive testing. The tests include abrasion, soundness, and petrographic analysis required to asses the suitability of the material for aggregate in concrete or bituminous concrete.

The preliminary muck evaluation is a very important step in the overall muck utilization planning effort for all types of muck. It establishes the potential uses and indicates the field and laboratory testing programs needed.

7.5.3 Complete Subsurface and Laboratory Testing

The completion of the entire field and laboratory soil and rock testing may require six months to two years. During this period, subsurface profiles should be prepared and examined as the borings are completed. Boring locations, depths, sampling and field testing procedures can be adjusted to meet unusual conditions.

As the detailed subsurface profile along the route is prepared, the laboratory testing program for final design and muck utilization can also be completed. The testing program for muck utilization will vary depending on the anticipated use for the muck. Generally, additional strength and compressibility tests will be required on remolded samples to develop the properties of the materials after placement. Tests for design information are normally conducted on undisturbed samples in order to assess the in-situ behavior of the soil and rock deposits. A discussion of the typical soil and rock testing program for design and muck utilization purposes is presented in Section 4 of this report.

7.5.4 Evaluate Probable Method of Construction and Muck Characteristics

Construction methods and equipment appropriate to soft or hard ground tunneling are described in Section 3. The method of excavation (e.g. TBM, drill and blast) influences muck characteristics. It is therefore necessary to determine which construction method or methods will be used before evaluating the potential uses for the muck.

The gradation of the muck is obviously affected by the method of mining, particulary in rock. However, dewatering problems in sand and gravel might be solved by grouting, freezing, dewatering, or using the innovative bentonite slurry tunneling machine. The selection of the equipment is normally determined by the contractor based upon past experience and the cost and availability of equipment. General guidelines for selection of tunneling equipment have been prepared [7-4]. The use or restriction of a particular method may be affected by factors such as noise and vibration control, settlement of adjacent structures, and economics (for example, mobilizing a TBM or freezing plant may be too expensive for a short section of tunnel). These problems are usually reviewed by the owner and the general engineering consultant during the design studies. After this review, the most likely alternates can be used to evaluate muck properties. The final estimate of muck properties thus depends on the method of construction and the typical soil and rock conditions.

Muck properties can be evaluated based on experience or, in the case of rock tunneling, use of an analytical method. The Muck Designation Number (MDN) is a new concept developed for determining the approximate range of grain size distribution for rock based muck [4-17]. The system is based upon a predictor equation which can be used to mathematically compute a number (i.e., the muck designation number) which is related to a particular range of grain size distributions. Variables used in the predictor equation are the in-situ rock properties (e.g. compressive strength, Schmidt hardness, dry unit weight) and the excavation system parameters, (e.g. for tunnel boring machine methods: thrust, advance rate, revolutions per minute; and for drill and blast methods: powder factor, explosives, drill round). The predictor equation was developed from a statistical analysis of approximately 50 case studies. A detailed discussion of muck characteristics including an example of MDN analysis is contained in Section 4 of this report.

7.5.5 Evaluate Potential Uses for Muck

The potential uses identified during the preliminary stage should be re-evaluated to confirm all technically feasible uses. The market value or economic feasibility of the alternative uses should be evaluated at a later stage.

For each of the alternative potential uses, the following information should be obtained:

a. Type of muck
b. Quantity
c. Anticipated quality
d. Standard for use
e. Processing equipment
f. Method of delivery, placement, and treatment

7.5.5.1 Type of Muck

Based on the subsurface profile and laboratory test data, the anticipated type of muck can be identified and carefully described. The basic muck categories used in this analysis include clay, sand and gravel, and rock-based muck. The test data indicate whether clay muck will be soft or stiff and whether sand muck is actually a silty sand or a clayey sand.

7.5.5.2 Quantity

The anticipated quantities of each muck type can be estimated from the subsurface profile and from the route alignment information.

7.5.5.3 Anticipated Quality

The laboratory data indicate whether rock samples have been highly weathered or if sand contains too much silt or clay to be acceptable for fine aggregate. Items such as pollution by groundwater or chemical wastes and the presence of construction debris must also be assessed.

7.5.5.4 Standard for Use

The specification requirements for each proposed use must be established. Many of the general requirements for landfill and specialized uses were presented in Sections 5-2 and 5-3. Landfill specifications may be tailored to the material and proposed land use and should be prepared for the specific tunnel muck product. Backfill specifications for the transit construction may impose different gradation requirements. These specification requirements must be established in order to accurately assess the feasibility of each alternative use.

It is suggested that representative samples of the materials be supplied to manufacturers or processors. The manufacturers can then complete special laboratory tests to determine the acceptability of the muck as a raw material. For example, a local brick manufacturer would be readily able to identify a good brick clay.

7.5.5.5 Processing Equipment

Basic processing of the muck should be evaluated. The methods include sorting, screening, crushing and washing and could be accomplished by the tunneling contractor at the portal area. A description of basic processing equipment is provided in Section 5-4.

7.5.5.6 Method of Delivery, Placement and Treatment

The method of transporting the muck from the portal to the utilization site should be considered. Methods include truck, train, and barge; truck is the most common.

When the muck is to be used in a landfill operation, the method of placement or future stabilization treatment should be considered. Initial placement and compaction required in controlled fills may not be possible. Surcharging or other stabilization methods may be required to permit full utilization of the landfill. Methods of soil stabilization are presented in Section 5-5.

7.5.6 Recommendations

The final recommendations should include all muck uses which are technically feasible. The methods of utilization should differentiate between landfill and specialized uses. The uses should also be ranked in order of the most probable schemes.

Recommendations should also be prepared which affect the preparation of the contract documents. For example, if sand muck is to be used for aggregate, then grouting may have to be prohibited as a method of groundwater control. If the muck is to be utilized in a special manufacturing process, then the responsibility for delivery and possibly the method of measurement (e.g. weight, volume) must be established.

The recommendations for muck utilization based on technical feasibility must then be incorporated into the overall planning process described in the following section.

8. MUCK UTILIZATION COORDINATING COMMITTEE (MUCC)

8.1 INTRODUCTION

The development and implementation of a muck utilization program requires three key elements: education, planning, and commitment.

8.1.1 Education

The transit authority and all organizations associated with the construction of the new system must realize the value of earth and rock materials removed from tunnels and foundation excavations. These materials should be treated as valuable construction materials rather than waste materials.

8.1.2 Planning

Planning of a muck utilization program must be initiated during the preliminary stages of project design so that the concept becomes an integral part of the design procedure. Lead time is required in order to complete a preliminary assessment and prepare recommendations for additional subsurface investigations and laboratory soil and rock testing. The utilization plans must be flexible. Alternative muck utilization programs must be prepared to provide for unanticipated changes in project construction schedules or construction methods or for other reasons.

8.1.3 Commitment

Commitment to the muck utilization program will be reflected by contract documents which no longer require the contractor to simply dispose of all excavated materials. Cooperation of local, city, state, and Federal organizations will greatly help the implementation of the program. Cooperation, however, must include a commitment to provide assistance and access to land or other services in accordance with the project schedule. Cooperation also applies to private industries who might be utilizing muck as a raw material in a manufacturing process.

The Muck Utilization Coordinating Committee will be responsible for implementing the goals of education, planning, and commitment.

8.2 ESTABLISH A MUCK UTILIZATION COORDINATING COMMITTEE

The transit authority contemplating a muck utilization program must delegate the organizational and planning responsibilities to staff members, planning agencies or consultants. In this report, the group is identified as the Muck Utilization Coordinating Committee (MUCC) and could be formed by the transit staff, city or state planning agencies, engineering consultants, or a combination. The organizational structure chosen for a particular project would depend on the local transit and government agency experience and capabilities. The transit authority should assume the leadership role in all cases.

In Chicago, for instance, the planning report prepared for the City of Chicago Department of Development and Planning recommended that the City of Chicago Department of Pubic Works act as the coordinating agency for the Lakefront Development. The recommendation was based on the department's technical capability, involvement in maintenance and repair of city property, and responsibility for design and construction of public projects including highways and subway construction. An alternative choice was the Chicago Park District, based on its past association and control of land development along the lakefront.

The following paragraphs outline the reasons for including a particular organization in the MUCC.

8.2.1 Transit Authority Staff

A muck utilization program directly affects the planning, design, and construction of a transit system. Since members of the transit authority staff are most familiar with the proposed system, the anticipated soil and rock conditions, the construction schedule, and the contracting practices, the transit authority should assume the leadership role in the muck utilization program. The transit authority will benefit from the utilization efforts by simplifying the bidding process and by eliminating environmental problems associated with indiscriminate muck disposal practices. These benefits are outlined in Section 7-2.

8.2.2 Government Agencies

Local planning boards or land development commissions should be included in the MUCC organization. A representative who is familiar with the overall regional land planning would be able to guide the land access and land use activities of the MUCC. Agencies in need of fill materials (e.g. highway department) and conservation groups should be encouraged to participate in order to improve communication and coordination efforts.

8.2.3 Consulting Engineer

On a major project, the transit authority normally retains an engineering firm to serve as the general consultant for the development and coordination of the design and construction of the entire system. The potential for utilization of muck or other excavated materials in the new construction must be considered by the consultant.

It follows, therefore, that a representative from the consulting engineering firm should participate in MUCC activities.

Alternatively, the transit property may prefer to retain a consultant because of lack of available staff, need for special expertise or an independent appraisal.

8.2.4 Funding of MUCC Activities

The manpower required to analyze the potential for muck utilization will naturally vary with the scope of the project. For a major project, such as the Chicago Deep Tunnel and Reservoir Project, the potential for community disruption resulting from muck disposal prompted the city planning department to retain a consultant to prepare a muck utilization program. In New York City, muck utilization planning has been completed by the Transit Authority (see reference to East 63rd St. tunnel in Section 6; p. 6-8).

Depending on the complexity and duration of the project and the number of general construction projects which might also be coordinated in the utilization program, the manpower requirements could range from one to three man-years. Financial support for the planning effort should be shared by the organizations such as the transit property, park development commission, harbors, highways and/or other public works agencies who will ultimately benefit from use of the material.

Federal support through multi-project grants should also be considered. If, for example, Federally supported recreational or housing projects will benefit from the use of muck for low cost fill, then a proportionate share of the muck utilization planning costs should be provided by a Federal grant.

8.3 INITIAL CONTACT AND DATA ACQUISITION BY MUCC

8.3.1 Public Land Development Projects

The short-and long-term land use planning for urban development must be reviewed. Tunnel muck is suited to many types of landfill projects which may be proposed by planning divisions, urban renewal, highway, airport, and other public organizations. The MUCC must survey these organizations to (1) educate the organizations about the value of muck and (2) develop feasibility guidelines. Low cost fill materials made available through urban transit construction may mean that abandoned development schemes can be reactivated.

8.3.2 Private Land Development

Private land development projects should also be investigated.

Land developers and contractors may be very receptive to the availability of fill materials in the urban area.

8.3.3 Overall Patterns of Construction Activity

The MUCC must be aware of other construction projects which may also result in a surplus of excavated materials. Other tunnel construction activities, harbor dredging, or general foundation construction could result in the need to organize a city-wide utilization plan or disposal program.

8.3.4 Specialized Uses

Local industries utilizing soil and rock materials as raw materials should be surveyed to determine basic requirements for the raw materials. The processors must be given time to consider the potential uses of soil and rock muck.

8.4 PLANNING RESPONSIBILITIES OF MUCC

The MUCC will be responsible for all planning related to muck utilization, including technical, scheduling, and contractural aspects. The final step in the planning process is the selection of one or more muck utilization schemes. All planning must be flexible.

The following paragraphs outline some of the general areas of planning responsibility.

8.4.1 Implement Utilization Guidelines

The MUCC must complete a technical evaluation of the muck properties including estimates of quantity and quality. The steps involved in the process are called the "utilization guidelines" and are described in detail in Section 7-5. Key utilization-guideline tasks are listed below for reference:

a. Establish route alignment and complete preliminary test borings.

b. Complete preliminary muck evaluation.

c. Complete subsurface and laboratory testing.

d. Evaluate probable method of construction and muck characteristics.

e. Evaluate potential uses for the muck.

f. Make recommendations.

By following these utilizations guidelines, the MUCC will determine the technically feasible uses for the excavated materials. The most promising three or four schemes should be selected for additional study. Final selection would be based on a benefit-cost analysis which would be conducted at a later stage in the evaluation process.

8.4.2 Market Analysis

The MUCC must evaluate the feasibility and economic planning details affecting the proposed utilization schemes. Practical engineering or construction problems must be solved, and the market value of the muck must be established.

As a first step, a basic approach has to be defined. Will the transit authority act simply as a supplier of materials or will it control the use of muck in the landfill or specialized use activity? For example, if the muck is technically suitable for use in an engineered, compacted fill, the transit authority may be able to utilize the material on the transit project and thus will have to control the placement and compaction operations. The muck could be sold as a fill material for use by other contractors, in which case the transit authority would have no interest in the final placement or compaction of the material. Similarly, the transit authority may or may not desire to process the muck to produce aggregate or track ballast. The MUCC must establish the goals of the utilization program. A flow chart Figure 8-1 illustrates the various options.

The feasibility and economic studies can be divided into two categories: (1) landfill schemes and (2) specialized uses. The feasibility and economic studies are used to determine the most practical and economic uses for the muck within each category. Checklists of feasibility and economic factors affecting utilization schemes are presented in Tables 8-1 and 8-2, respectively. These suggested checklists may be expanded or modified to satisfy local needs.

It is apparent that selection of the option to simply supply muck as a construction material involves a minimum of planning effort. This applies to both the landfill and specialized uses schemes. This option is desirable because of its inherent simplicity, provided the muck qualifies as an acceptable material.

The final product of the feasibility and economic study consists of a list of three or four muck utilization programs ranked according to feasibility and cost.

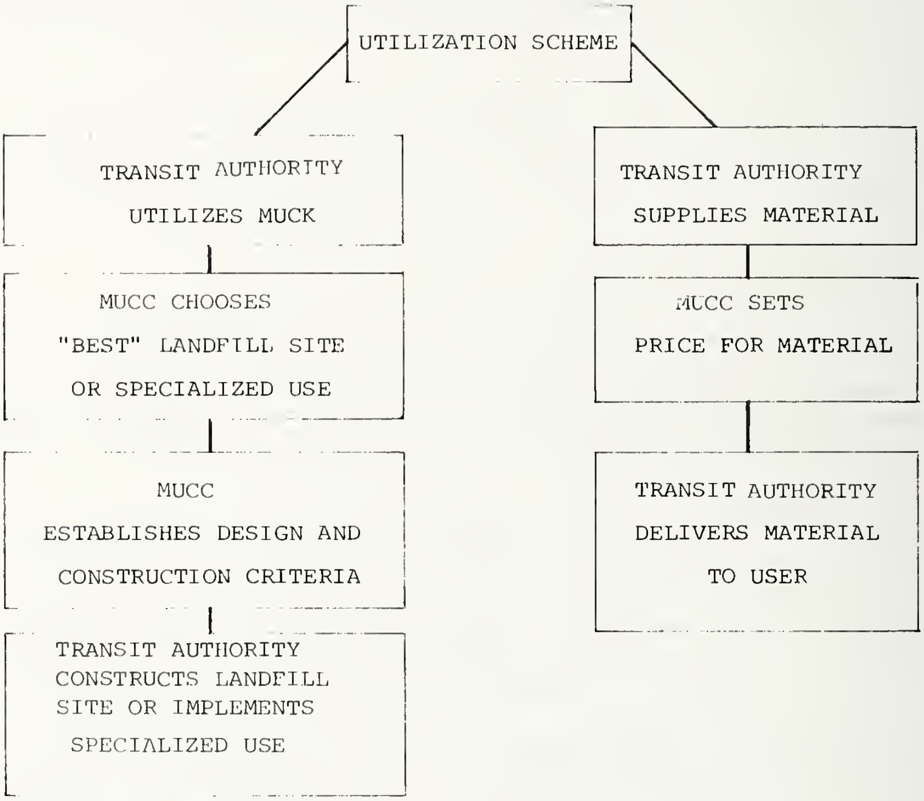

UTILIZATION SCHEME
TRANSIT AUTHORITY UTILIZES MUCK
MUCC CHOOSES "BEST" LANDFILL SITE OR SPECIALIZED USE
MUCC ESTABLISHES DESIGN AND CONSTRUCTION CRITERIA
TRANSIT AUTHORITY CONSTRUCTS LANDFILL SITE OR IMPLEMENTS SPECIALIZED USE
TRANSIT AUTHORITY SUPPLIES MATERIAL
MUCC SETS PRICE FOR MATERIAL
TRANSIT AUTHORITY DELIVERS MATERIAL TO USER

FIGURE 8-1. FLOW CHART OF MUCK UTILIZATION OPTIONS

TABLE 8-1. FEASIBILITY AND ECONOMIC FACTORS AFFECTING LANDFILL UTILIZATION SCHEMES

I. OPTION: Landfill Operated by the Transit Authority

A. Available Sites

1. Locate available sites, including transit property projects
2. Determine present ownership; public vs. private
3. Establish land value - purchase price
4. Complete site evaluations - wet or dry, coastal, etc.
5. Establish zoning and/or environmental restrictions

B. Intent of Landfill

1. Predict potential land use: park, business, residental
2. Estimate land value after filling

C. Site Development

1. Determine steps required to prepare site for filling
2. Prepare design and construction controls, estimate quantity, placement, and treatment methods
3. Identify factors affecting construction - e.g. truck routes, noise, etc.

D. Development Costs

1. Establish market value for muck fill compared to other sources (i.e., gravel pit, quarry, etc.)
2. Estimate Land development costs using muck compared to other sources

II. OPTION: Landfill Operated by Others

A. Market Demand for Materials

B. Supply Price of Materials

1. Establish market price for muck supplied "as-is".
2. Establish market price for muck which has been processed, i.e., sorted, screened, washed, etc.

TABLE 8-2. FEASIBILITY AND ECONOMIC FACTORS AFFECTING SPECIALIZED USES

I. OPTION: Transit Authority Processes Muck

A. Product Use

1. Identify potential uses: track ballast, concrete aggregate, bituminous concrete aggregate, etc.
2. Establish quality control requirements

B. Processing Equipment

1. Identify equipment: sorting, screening, crushing, etc.
2. Locate Processing site and stockpiling area
3. Determine operational requirements: power, labor, etc.

C. Production Costs

1. Establish market value of processed muck and compare with commercial products

II. OPTION: Transit Authority Supplies Raw Materials

A. Raw Materials

1. Survey possible users to determine need for the muck "as-is"
2. Establish quality requirements, if any, for each use

B. Price of Materials

1. Determine transportation costs
2. Establish market price of muck "as-is"

8.4.3 Prepare Contingency Plans

It is difficult, if not impossible, to predict all possible variations in the design, funding, and construction process which could affect the muck utilization program. The key factor is flexibility. Contingency problems, identified in Section 6, are summarized below for reference:

a. Subsurface conditions

b. Method of construction

c. Delays in construction program

d. Utilization specifications

Alternative muck utilization programs must be prepared by the MUCC in order to provide a smooth transition between programs, if one scheme were abruptly canceled. In this way, the transit authority does not lose control of the situation and thereby jeopardize the normal owner-contractor relationship. Additional recommendations for contract documents are presented in Section 8.6.

Alternative utilization programs may be required to deal with anticipated changes in muck properties or with delay in muck production due to postponement of funding allocations or construction problems. The transit authority may be able to locate landfill sites requiring engineered, compacted fill and other sites requiring only common fill. Stockpiling is an effective way to provide a source of material for processing through a portable screening and crushing plant.

Through the contract documents the owner maintains control of the muck utilization program. The documents must be clearly written to indicate that alternative disposal areas can be made available to maintain a continuous muck disposal program. A careful analysis of potential problems combined with a flexible utilization program will enable the MUCC to handle contingency problems.

8.4.4 Environmental Planning and Public Relations

A muck utilization program indicates to the public that the transit authority is concerned with the disposal of excavated materials and is anxious to eliminate the adverse effects of an uncontrolled disposal program.

For each of the proposed utilization schemes, particularly the landfill programs, the MUCC must assess the potential environmental impact. In terms of the transit construction activities, the MUCC can publicize the fact that excavated materials will be utilized and not simply dumped in the river. During the preparation of the EIS statement, for example, the MUCC on behalf of the transit authority can outline preliminary utilization plans, thus promoting the concept of utilization from the start of the project.

The MUCC will have to inform local environmental groups of the plans for utilization and deal with the objections of these groups. However, by starting the entire planning process early in the design program, last minute environmental problems will be avoided.

A checklist of Federal, state, and local agencies who may be concerned with environmental planning is shown in Table 8-3. Local or regional agencies will probably be more concerned with the details of a utilization program, particularly if landfill schemes are involved.

TABLE 8-3. AGENCIES CONCERNED WITH ENVIRONMENTAL PLANNING FOR URBAN TRANSIT SYSTEMS

1. U.S. Department of Transportation, Assistant Secretary for Environment, Safety and Consumer Affairs

2. The Council on Environmental Quality

3. Environmental Protection Agency, Regional Office

4. Department of Housing and Development, Regional Office

5. Department of Interior

6. Department of Health, Education and Welfare

7. Department of Agriculture

8. Department of Commerce
    - Economic Development Administration
    - Office of Economic Opportunity

9. Army Corps of Engineers

10. Federal Highway Administration, Regional Office

11. State Clearinghouse: Office of Planning and Budget

12. Regional Clearinghouse: Regional Commission

13. State Government: Land Planning and Soil Conservation Service, Department of Natural Resources

14. County Government: (Land Planning) County Engineering, Department of Public Works

15. City Government: (City Planning) City Engineering, Department of Public Works

8.4.5 Permits and Approvals

In order to avoid last minute delays, the MUCC must investigate the need for special permits or approvals to conduct landfill or other processing operations. Landfill operations, for instance, may have to meet building code requirements (compaction requirements or building permits) or satisfy gravel pit restoration requirements (grading of finished surface) or approval of a park or public works department.

Restoration of sand and gravel pits in Prince George's County, Maryland, requires the preparation of plans showing final contours and the provisions of erosion control during restoration operations. Since men and equipment will be working at the site, an occupancy permit is needed [8-1]. Many city and county governments require hauling permits for trucking over secondary roads and guarantee bonds for maintenance or repair of roadways.

The MUCC must identify the permits required for each proposed utilization scheme. Eventually the transit authority should obtain the permits for the utilization schemes which are finally selected for implementation.

8.4.6 Benefit-Cost Analysis

The completion of a benefit-cost analysis provides the MUCC with additional information to help in the final determination of the muck utilization program. The actual cost and benefit figures may be based on estimates or qualitative judgments, but completion of the analysis will have a net positive effect.

The actual cost of producing the muck in the tunnel is unaffected by the muck utilization program. In the normal contracting practice, the contractor is required to dispose of all excavated materials outside the right of way. The cost of disposal is passed on to the owner as part of the excavation price. The muck utilization program affects this hidden contract cost. During the planning stage, the disposal costs must be estimated. The real cost can only be confirmed by establishing alternative bid items in the bid documents. An example of alternative bid items is shown in Figure 8-2. The differential between the options, utilization program versus contractor disposal, establishes the immediate benefit or cost to the transit authority. The MUCC must consider these factors when evaluating the effect of the muck utilization program on the transit construction cost.

A benefit-cost analysis typically produces three options:

a. Costs less than benefits; program accepted.

b. Costs exceed benefits but benefits are high; program accepted.

c. Costs greatly exceed benefits; program not accepted.

Referring to Figure 8-2, it is apparent that if the unit price for Method A or B is less than the price of contractor disposal, then the utilization program will be accepted. If the cost of the utilization program falls into Method B, then the benefits of the utilization program must be evaluated. Alternatively, the additional cost may be absorbed by special funding grants or by offsetting payments from other agencies.

Consider the following example. Method A involves the development of a city park area. Alternative bids indicate an additional cost of $2.00 per unit volume for the utilization program compared to disposal by the contractor. The city cannot buy fill at a price lower than $4.00 per unit volume, and is therefore willing to pay the transit authority the $2.00 differential.

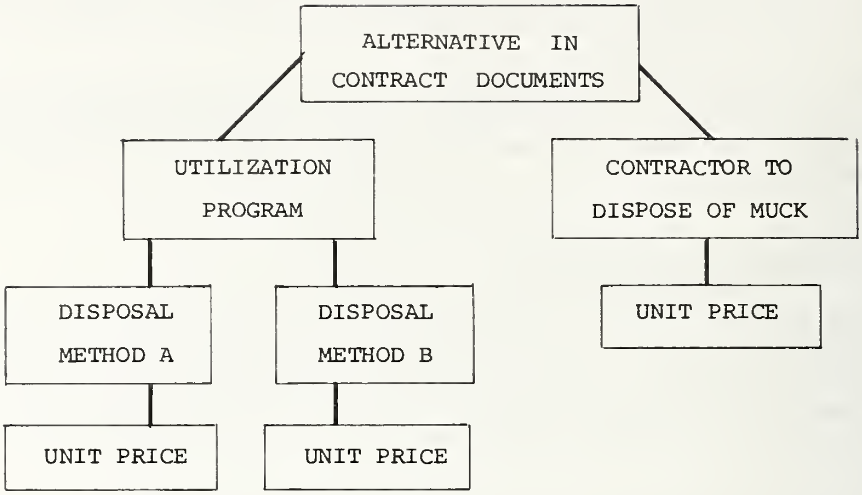


FIGURE 8-2. ALTERNATIVE MUCK UTILIZATION BID ITEMS

When utilization program costs greatly exceed the contractor disposal price, then the utilization program is not accepted.

The benefits associated with Methods A and B must be determined by the MUCC, using a qualitative, semi-economical benefit-cost analysis. The market analysis will have already identified those schemes consistent with local construction and manufacturing capabilities. Basic costs are also available, measured, for instance, by purchase of land or equipment. Benefits may be more difficult to quantify, particularly when environmental, recreational or restoration values are introduced. A landfill used for an industrial park or shopping center can be evaluated in terms of increased tax base, job opportunities, etc. Recreational area or environmental improvement is assessed in terms of community needs. By investing time and money in environmental considerations, the transit authority may find that the resulting goodwill increases community acceptance of the project, particularly during the construction period when traffic and business activities are disrupted.

8.4.7 Selection of Muck Utilization Alternatives

The final planning step involves the selection of three or four alternative utilization schemes. At this stage, the MUCC will have accumulated sufficient quantitative data to make a realistic appraisal of the alternatives and to make realistic, practical decisions.

8.5 SCHEDULING RESPONSIBILITIES OF MUCC

8.5.1 Limitations of Control

The actions of Federal, state and local agencies are beyond the control of the MUCC. The MUCC must maintain liaison with the critical government agencies to convince them of the validity of the muck program and the need to coordinate planning, funding, and construction activities. In the final analysis, however, major shifts in Federal funding allocations or state or county land use requirements may drastically affect the overall transit construction schedule. The muck utilization program must be flexible enough to absorb these shifts in government policy.

8.5.2 Establish Utilization Program Time Schedule

Preliminary construction schedules can be used to coordinate muck utilization programs. Wherever possible, the final program schedule should be established after major transit planning and funding policies have been confirmed. The MUCC can then coordinate the rate of muck production from transit construction activities with the muck processing or landfill construction schemes. In order to account for variations in the daily rate of muck production, scheduling may have to be based on average weekly or monthly construction activities. The timing must be established, but it must not be so rigid that construction delays cause the utilization program to collapse.

8.5.3 Interagency Coordination of Construction Schedules

In order to insure maximum benefit from the muck utilization program, the MUCC must coordinate construction activities among the transit authority, other government development projects, and the private sector. Based on the data obtained from a general analysis of public and private construction activities, the MUCC must prepare a more detailed coordination plan. If the transit authority is to supply fill material for a highway project, then the highway department must be able to provide the disposal area. Calendar dates must be established and written commitments must be obtained. These written commitments will force each agency to realistically evaluate its own schedules and eliminate problems after transit construction has been started.

8.6 CONTRACT DOCUMENTS

The MUCC must either prepare the contract provisions for muck utilization or else provide recommendations which will help others prepare the contract documents. In both cases, the MUCC must review the final contract package for consistent muck utilization planning.

8.6.1 Information Package

The contract documents must clearly outline the owner and contractor roles in the utilization program. An information package should be included in the documents or issued separately. The package would contain a description of the project, a list of participants other than the transit authority, plans indicating the location of the disposal sites and acceptable trucking or transportation routes, a list of permits required for the work (identifying those permits to be obtained by the owner) special instructions for sorting or processing the muck at the tunnel portal, special test data, and other significant information.

8.6.2 Alternative Bid Items

Specifications have typically required the contractor to submit a unit price which includes excavation and disposal of soil or rock. With the introduction of the muck utilization program, the procedure must be changed to require separate prices for excavation and disposal. The muck utilization program will form the base bid item for disposal while the standard disposal by the contractor will become the alternative. A sample bid comparison sheet is shown in Table 8-4. The format and number of alternatives can be changed to suit any special requirements.

I. Base Bid: Utilization Program

Scheme	Description	Estimated Quantity cu yd	Deliver to Site Unit Price
A	Engineered, Compacted Fill	75,000	
B	Aggregate	50,000	
C	Controlled Fill (General Disposal)	125,000	
	Total Volume:	250,000	

II. Alternate Bid: Disposal by Contractor

A	Disposal by Contractor	250,000	

TABLE 8-4. COMPARISON BID SHEET FOR DISPOSAL OF EXCAVATED MATERIALS

8.7 ADMINISTRATION OF MUCK UTILIZATION PROGRAM

Administration of the muck utilization program can be accomplished either by the MUCC or through the normal contract administration process. The choice will depend on the complexity of the muck disposal process.

If, for example, the muck is sold as a fill material and no elaborate processing is required, then control of the program can be delegated to the construction supervision staff which will maintain records of quantities for payment purposes. On the other hand, if the muck will be stockpiled on transit property for future processing (e.g. crushing for ballast) then the utilization program may extend beyond the completion of tunnel construction. In this case, administration of the program should be delegated to the member of the MUCC representing the transit authority.

9. HANDBOOK EVALUATION

9.1 INTRODUCTION

The detailed investigation of muck utilization potential presented in Sections 2 through 8 of this report has been summarized into a handbook which provides a concise description of muck utilization planning concepts.

Prior to its final preparation, the handbook was reviewed by various transit authority management personnel and other individuals involved with tunnel muck utilization planning. Their comments and suggestions were considered and appropriately incorporated into the handbook. The remaining portion of this section documents this review.

9.2 DISTRIBUTION AND RESPONSES

During the period from December 1975 to January 1976, draft copies of the handbook were sent to 19 people. The list of reviewers was compiled with the help of the Transportation Systems Center in Kendall Square, Cambridge, Massachusetts.

Approximately 85 percent of the handbooks were distributed to transit authority directors and/or management personnel within the major U.S. cities. The remaining copies were distributed to various educational and governmental agencies.

Eleven individuals, eight from transit authorities and three from educational and governmental agencies, commented in writing on the handbook. Table 9-1 lists these responding individuals. On occasion, the transit authority directors delegated the handbook review to Chief Engineers or other similarly positioned personnel.

9.3 EVALUATION

The handbook reviewers generally exhibited a favorable view towards muck utilization. The agencies agreed that muck utilization planning was beneficial and should be included in the overall development of a transit tunnel project. Some reviewers implied that early formation of the planning concepts and implementation in the contract specifications is important. One reviewer described the successful use of transit tunnel muck as fill and riprap. Other reviewing transit agencies indicated that they intend to implement muck utilization planning efforts, similar to those presented in the handbook, during their future projects. As a result of reading the handbook, the Baltimore Mass Transit Administration recently agreed to participate in a trial case study of muck utilization planning. The results of this case study are described in Section 10.4 of this report.

TABLE 9-1. LIST OF INDIVIDUALS RESPONDING TO HANDBOOK REVIEW

	Agency	Contact Person
I.	Transit Authority	
1.	Mass Transit Administration Baltimore, Maryland	Frank Hoppe, Director of Engineering and Construction
2.	Chicago Urban Transportation District, Chicago, Illinois	Harold E. Nelson, Executive Director
3.	Southeast Michigan Transit Authority, Detroit, Michigan	William V. Seifert, Chief of Engineering
4.	Southern California Rapid Transit District, Los Angeles, California	Richard Gallagher, Manager Rapid Transit Dept. and Chief Engineer
5.	New York City Transit Authority, Brooklyn, New York	John F. Cohane Deputy Chief Engineer
6.	Bay Area Rapid Transit District, San Francisco, CA	William McCutchen Manager of Installations
7.	Washington Metropolitan Area Transit Authority, Washington, D. C.	Vernon Garret, Jr. Director, Office of Engineering
8.	Niagara Frontier Transit Authority, Buffalo, New York	Kenneth G. Knight General Manager, Metro Construction
II.	Government and University	
1.	Environmental Protection Agency Washington, D. C.	Rebecca Hammer Acting Director Office of Federal Activities
2.	University of Massachusetts Department of Geology Amherst, Massachusetts	Dr. Oswald C. Farquhar Professor of Geology
3.	Colorado School of Mines Golden, Colorado	Dr. Robert Faddick Associate Professor

Additional comments by the reviewers in support of muck utilization planning are summarized below:

a. A beneficial use of waste materials.

b. Environmental pressures represent an incentive for muck utilization.

c. The additional cost of geotechnical work required for muck utilization would benefit the entire project.

d. Muck utilization can reduce contract bid price and overall spending by the transit authority.

While most comments were favorable, some negative comments were made as well. Most notable are the following:

a. The unpredictable Federal government scheduling of money grants hinders commitment by others for muck utilization.

b. Specialized uses are not feasible unless the local industry already exists within the community.

c. Implementation guidelines appear to be too elaborate.

d. Transit agencies may be reluctant to invest money in muck utilization planning if there is no commitment for implementation.

One reviewer reported his transit authority's attempt to develop a program of muck utilization in the beginning of the transit tunnel project. Additional geological studies such as aerial surveys of potential disposal sites were employed. Potential uses of muck, including a variety of schemes for establishing suitable disposal areas and another scheme to convert the excavated rock to crushed stone, were investigated. However, after the planning effort had been exhausted, the transit authority concluded that "any effort to control and utilize the deposit of muck or waste would result in expense to the Authority." The reviewer identified the following difficulties with the planning efforts.

a. No firm commitment could be secured from owners of potential disposal areas. Coordination between public and local groups was lacking from the planning efforts.

b. In order to offset the potential maintenance cost for a transit authority-owned disposal site, a dumping fee had to be assessed to the hauling contractor. The dumping fee was passed back to the Authority in the form of higher bid prices, therefore reducing the potential savings due to muck utilization.

c. Some hauling contractors sold the excavated muck which was reflected in their lower bids to the Authority.

d. No economic feasibility study to assess the cost benefit of the muck utilization schemes was undertaken.

However, the reviewer did favor the muck utilization plannig concepts identified in the handbook. He stated that "a Muck Utilization Coordinating Committee, as recommended in the handbook, is a satisfactory approach to a unified planning effort."

10. MUCK UTILIZATION PLANNING - THREE CASE STUDIES

10.1 INTRODUCTION

Muck disposal planning efforts were investigated for three cities: Chicago, Atlanta, and Baltimore. Transit agencies in each of these cities are either expanding existing or constructing new rapid transit systems. The study examined current methods used to solve the problems related to muck disposal in urban areas. As an extension to the initial review of the proposed Baltimore project, the planning concepts described in this report were implemented and a muck utilization plan was developed for the proposed rapid transit construction in Baltimore. The general scope of the muck disposal problem for each city is summarized below:

a. Chicago: Extension of the subway system plus the construction of a deep tunnel and reservoir system will produce an astounding 184 million cu yd of muck over a 15 year period. A long-range muck disposal planning effort was completed by the City of Chicago Department of Development and Planning. The plan calls for construction of lake-front landfill utilizing muck from all major transit and tunneling projects.

b. Atlanta: The construction of the new rail transit system by the Metropolitan Atlanta Rapid Transit Administration will produce about 7 million cu yd of muck. About 25 percent of the muck will be acceptable for use in construction. It is anticipated that the remaining excess material will be utilized as fill in local construction and landfill projects.

c. Baltimore: The Mass Transit Administration is completing plans for a new transit system involving tunneling, cut and cover, and at grade construction. An estimated 2 million cu yd of excavated material will be produced during the construction. It is likely that the muck will consist of sand and gravel material acceptable for aggregate or landfill projects.

10.2 NO. 1 - CHICAGO, ILLINOIS

10.2.1 General

Within the City of Chicago, the general contractor traditionally has been responsible for the disposal of tunnel muck. In the past, landfill areas have generally been available for disposal sites. Such areas have included the north section of Lake Shore Drive (1920's), Lincoln Park area (1940's), and more recently, O'Hare Airport. O'Hare Airport has been a major focal point for muck disposal, and oftentimes haul routes to the area have been specified by the airport authority. A proposed O'Hare Airport extension into Lake Michigan was not approved because of environmental considerations.

As a result of the planned construction of several projects in the Chicago area, the City of Chicago Department of Development and Planning (CCDDP) has recently undertaken a major planning effort to investigate the potential utilization of the anticipated large volumes of muck.

10.2.2 Summary

It is anticiapted that within the next few years, a volume of material in excess of 184 million cu yd will be made available from construction within the Metropolitan Chicago area [10-1].

Project Name	Agency	Estimated Spoil Volume (million cu yd)
1. Deep Tunnel & Reservoir Project (DTRP)	Metropolitan Sanitary District of Greater Chicago (MSDGC)	179.0
2. Chicago Central Area Transit Project (CCATP)	Chicago Urban Transit District (CUTD)	2.7*
3. Dredging (10 yr. period)	U.S. Army Corps of Engineers (CE)	2.7
		184.4

Note: *Recently updated to 4.3 by the Chicago Urban Transit District [10-2].

After estimating the quantities and types of muck and evaluating their potential uses, the CCDDP contacted various agencies and discussed with them the problems of muck utilization. Besides landfill, use of muck for manufacturing portland cement and aggregate and for agricultural purposes was investigated.

The study concluded that the muck could most profitably be used for lakefront development. Chemical analysis of the rock showed it to have an amount of magnesium oxide far in excess of ASTM standards for portland cement. Producing aggregate and agricultural products with the available supply of muck would seriously oversupply Chicago markkets and possibly cause commercial suppliers to go out of business. River and harbor dredgings, particularly those containing environmentally harmful materials, are very difficult to utilize even as landfill. CCDDP has proposed a disposal scheme for such materials.

10.2.3 Project Descriptions

Most of the muck will be produced by the Metropolitan Sanitary District of Greater Chicago (MSDGC) Tunnel and Reservoir Projects. The deep reservoir and tunnel project will eliminate overflow of the combined sewage and storm water system into surface waterways. The recommended Chicago Underflow Plan consists of three main tunnel systems, Des Plaines, Mainstream, and Calumet which fork out from the primary reservoir facility located at McCook-Summit area [10-3]. The tunnels, ranging in diameter from 10 to 42 ft, have a total length of 120 miles. The main reservoir system will be 330 ft deep, 500 to 1200 ft wide, and approximately 2.5 miles long. It will consist of three basins having a total storage capacity of 91.2 million cu yd. Figure 10-1 shows the location of the major tunnel systems and reservoirs.

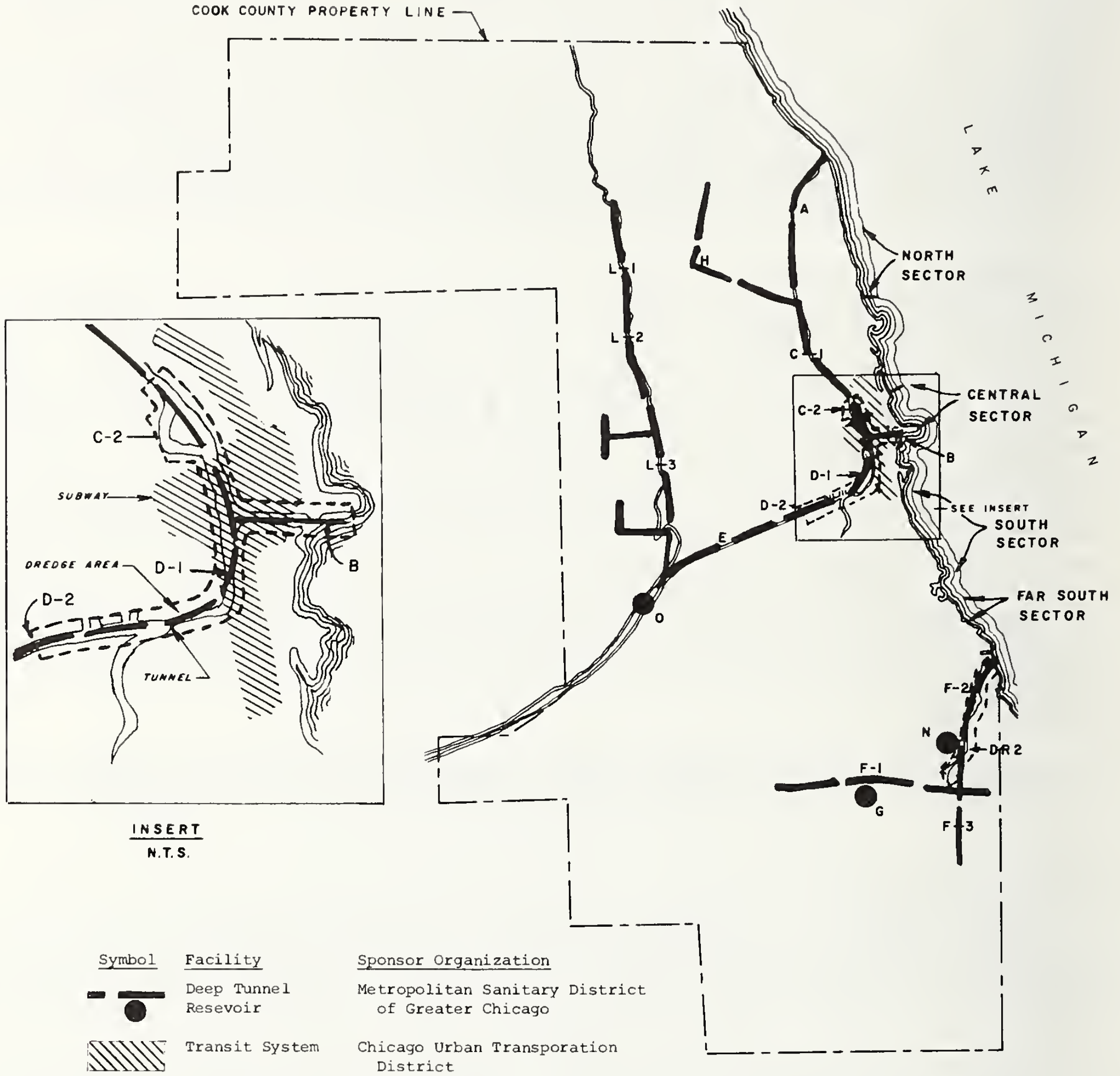
Based on a 1968 study, the Chicago Urban Transportation District (CUTD) has recently completed plans for a 15.2 mile extension of the existing subway system. This system, expected to be completed over a ten year construction period, will replace the existing elevated "Loop" system. The first phase of construction involves a 2.8 mile east-west distributor line and a 4.7 mile subway. Seventy-five percent, or 5.7 miles, will be cut and cover construction, and the remaining 1.8 miles will be deep tunneling. Corps of Engineer (CE) dredging of existing river and harbor facilities is the last major source of excavated material for landfill development. The dredging, part of a general maintenance and improvement program, has been temporarily suspended because of the lack of economically available sites for dredged spoil disposal. Reactivation of dredging operations is contingent upon the successful development of a satisfactory disposal method. Figure 10-1 also indicates the primary locations of dredging operations.

In addition to these three major projects, excavated materials may become available through normal construction activity.

10.2.4 Geology

The projects will produce both soil and rock materials. The soil deposits consist of a surface artificial fill underlain by Pleistocene deposits of lacustrine clays and sands, glacial till, and outwash sands and gravel. The underlying rock strata consist of dolomitic limestone and shale. The MSDGC Tunnel and Reservoir Project will be primarily constructed in the rock deposits; relatively small portions of the surface reservoir systems and tunnels will be constructed through the overburden soil deposits.

The transit subway system will be constructed in the clayey glacial till deposits. The shallow tunnel alignments and the cut-and-cover sections will encounter sand and silt materials in addition to rubble fill. The dredged spoil materials derived from Calumet Harbor, Chicago Harbor, Chicago River, and North Branch Canal are contaminated. Unusually high concentrations of phosphorous, ammonia, phenol, zinc, sulfide, oil, and grease exist in the river and harbor bottom sediments. In addition, high percentages of volatile solids and COD have been found. These materials are considered environmentally harmful and could pollute fresh water supplies if poor disposal methods were employed.



Symbol	Facility	Sponsor Organization
▬ ▬ ●	Deep Tunnel Resevoir	Metropolitan Sanitary District of Greater Chicago
▨	Transit System	Chicago Urban Transporation District
----	River and Dredging	Corps of Engineers

Note: Refer to Figure 10-4 for identification of lettered areas shown on location plan

FIGURE 10-1. SECTOR LOCATION PLAN FOR LAKEFRONT DEVELOPMENT [10-1]

SOURCE: KBS; Exhibit 1

10.2.5 Methods of Construction

Depending on the soil or rock conditions, different construction methods will be used for each of the projects.

Excavation of the tunnel and reservoir system will be accomplished by TBM for the smaller diameter tunnels and conventional drill and blast for the larger tunnels. Use of a new TBM capable of driving 35 ft diameter tunnels is contemplated.

Excavation of the large underground reservoirs will be accomplished by drill and blast methods similar to open quarry pit methods, such as bench blasting.

The transit tunnel system consists of deep to shallow subways, at grade, and aerial structures. Depending on the economics, either shield excavation tunneling or cut-and-cover methods will be used. Clam shell digging or hydraulic pumping methods will probably be used to dredge the river and harbor areas.

10.2.6 Types of Muck

An estimate, based on 1973 design concepts, indicates a potential volume of muck in excess of 184 million cu yd. Most of the muck will consist of dolomitic limestone from the deep tunnel system. Glacial till, sands and gravels, and clay materials will be produced from the subway construction.

Laboratory tests on intact samples of dolomitic limestone indicate compressive strengths ranging from 15 to 20 ksi. Table 10-1 summarizes the chemical composition of the rock.

The rock muck produced from the TBM will range from chips to dust size particles; drill and blast will yield rock muck ranging from boulder and cobble sized material to fine sand size. Other materials from the tunnel and reservoir system will include glacial till, rock, shale, and possibly large boulder and cobble sized stone.

Tunnel muck from the transit system is primarily a clay-based glacial till. These materials, which have high strengths and low compressibility in an in-situ undisturbed condition, will show opposite characteristics when disturbed. Their gradation characteristics will remain fairly unchanged.

A chemical analysis of the dredge spoil material is given in Table 10-2. For purposes of comparison only, EPA Water Quality Standards are also shown.

10.2.7 Potential for Utilization of Excavated Material

Plans for the utilization of excavated materials within the Chicago area have been prepared by (1) the City of Chicago Department of Development and Planning and (2) by various owner-organizations. The proposed utilization plans are summarized in the following Section 10.2.7.1 and 10.2.7.2.

TABLE 10-1. CHEMICAL ANALYSIS OF SILURIAN FORMATION [10-1]

SOURCE: KBS; p. 28

	Typical Values	
Constituent	Niagarian Racine	Alexandrian Kankakee
% loss on ignition	50.2	43.5
% Silicon dioxide	0.5	4.3
% Aluminum oxide	0.01	1.3
% Iron oxide	0.8	1.9
% Calcium oxide	28.4	27.8
% Magnesium oxide	19.6	18.6
% Carbon dioxide	49.5	42.7
% Potassium oxide	0.01	0.08

TABLE 10-2. CHEMICAL ANALYSIS OF CALUMET RIVER DREDGE SPOIL [10-1]

SOURCE: KBS; pp. 31, 35

Constituent	Average	EPA Water Quality Standard
% of Total Solid	53.1	-
% of Volatile Solid	9.8	-
COD (mg/kg)	82,000	35
Total P (mg/kg)	847	0.05
Sol-P (mg/kg)	2.86	-
NH_3-N (mg/kg)	123	1.5
NO_3-N (mg/kg)	1.03	10
Org-N (mg/kg)	1950	-
SO_3 (mg/kg)	88	-
Phenol (mg/kg)	4429	100
Oil & Grease (mg/kg)	5899	10
Total Fe (mg/kg)	5420	1.0
Copper (mg/kg)	75	.02
Nickel (mg/kg)	51	1.0
Zinc (mg/kg)	688	1.0
Lead (mg/kg)	188	0.1
Chromium (mg/kg)	76	-

10.2.7.1 Recommendations By City of Chicago Department of Development and Planning

Much of the rock to be excavated from the deep tunnel and reservoir project is ideal for the production of aggregate and agricultural ground limestone. It is anticipated that the rock excavated by the TBM's would be too fine for use as aggregate, whereas the drill and blast operations would yield a rock spoil suitable for crushing or direct processing. In fact, many commercial suppliers in the Chicago area operate quarries in the dolomitic limestone deposits. However, the extremely large quantities of material estimated from the reservoir excavation alone would flood the market and put many of the local suppliers out of business. The CCDDP therefore concluded not to go into a full scale production of aggregate, which in the long run, would significantly depress the aggregate market at the expense of the commercial suppliers.

The production of portland cement from the dolomitic limestone was also considered, but the chemical analysis of the rock, shown previously in Table 10-1, indicated a magnesium oxide content far in excess of the ASTM standard specification (ASTM C150). This factor made it unfavorable to economically utilize the rock for portland cement production.

The utilization plan finally adopted by the CCDDP was a landfill program concentrated on the development of lakefront areas along Lake Michigan. The opportunity to increase the economic value of these areas while providing for long-term utilization of great quantities of excavated material was the primary reason for this decision. The overall objectives of the proposed lakefront land development program are listed below:

a. Provide shoreline protection from wave action.

b. Increase land areas and protected water for public recreational use.

c. Provide wildlife refuge.

d. Generally improve the quality of urban living for the people in Chicago.

e. Provide an opportunity to reactivate Corps of Engineers dredging for improvement of the river and harbor areas.

f. Provide a readily available disposal site for contractors.

The broad range of the program was designed to attract the interest of as many parties as possible. A brief description of the landfill scheme follows.

The scope of the planning effort consisted of: (1) approximating quantities, types, and general availability of excavated materials,

(2) postulating various landform shapes and possible construction locations along the lakefront area, (3) evaluating the effects of physical and economic constants on the design of each land form, (4) estimating costs for the various landfill schemes, and (5) estimating the unit cost for disposal of excavated material at the lakefront areas for each of the participating organizations.

Four alternative land forms were considered:

Alternative I: Parallel extension of existing shoreline

Alternative II: Construction of peninsula

Alternative III: Peninsula construction with provisions for a small boat harbor

Alternative IV: Construction of off-shore islands

The type of land form constructed in a particular area depended on a number of factors. The volume of fill needed to develop an area of surface land and the cost of protective breakwaters increase significantly with greater water depths. The availability of a sufficient amount of landfill materials at a reasonable cost further control the type of land form to be constructed. Other influencing factors are the cost of installing utility services, accessibility of the landfill site during construction and to the public after completion, and orientation of the landfill with respect to wind direction and waves (e.g., erosional effect on protective breakwaters).

Based on these general considerations and limited subsurface exploration data, four study areas were designated as possible locations for landfill sites. The locations of these areas, designated North Sector, Central Sector, South Sector, and Far South Sector are shown in Figure 10-1. In addition, several landform configurations were prepared for each sector. A typical configuration plan for the South Sector is illustrated in Figure 10-2.

A preliminary engineering effort was made to determine the most economical type of protective breakwater system, including impermeable double-walled breakwater, cellular sheet pile enclosures, single wall sheet piling with tiebacks, and rubble mound protective enclosures. Estimated costs were established for each type of enclosure. It was concluded that utilization of the drill and blast rock spoil from the tunnel and reservoir project and till materials from the transit system made the rubble-mound type breakwater the most economical structure, independent of water depth.

An important phase of the planning effort by CCDDP involved the consideration of an impermeable type of enclosure to be used for disposal of the highly contaminated river and harbor sediments expected from the Corps of Engineer's dredging operations. The landfill scheme shown in Figure 10-3 was developed for the biological treatment of these sediments. Biological degradation, very similar to methods employed in sewage treatment plants for secondary treatment operations, occurs as the contaminated water trickles through the broken rock. Rock muck from the tunnel and reservoir project will be utilized as the trickling medium.

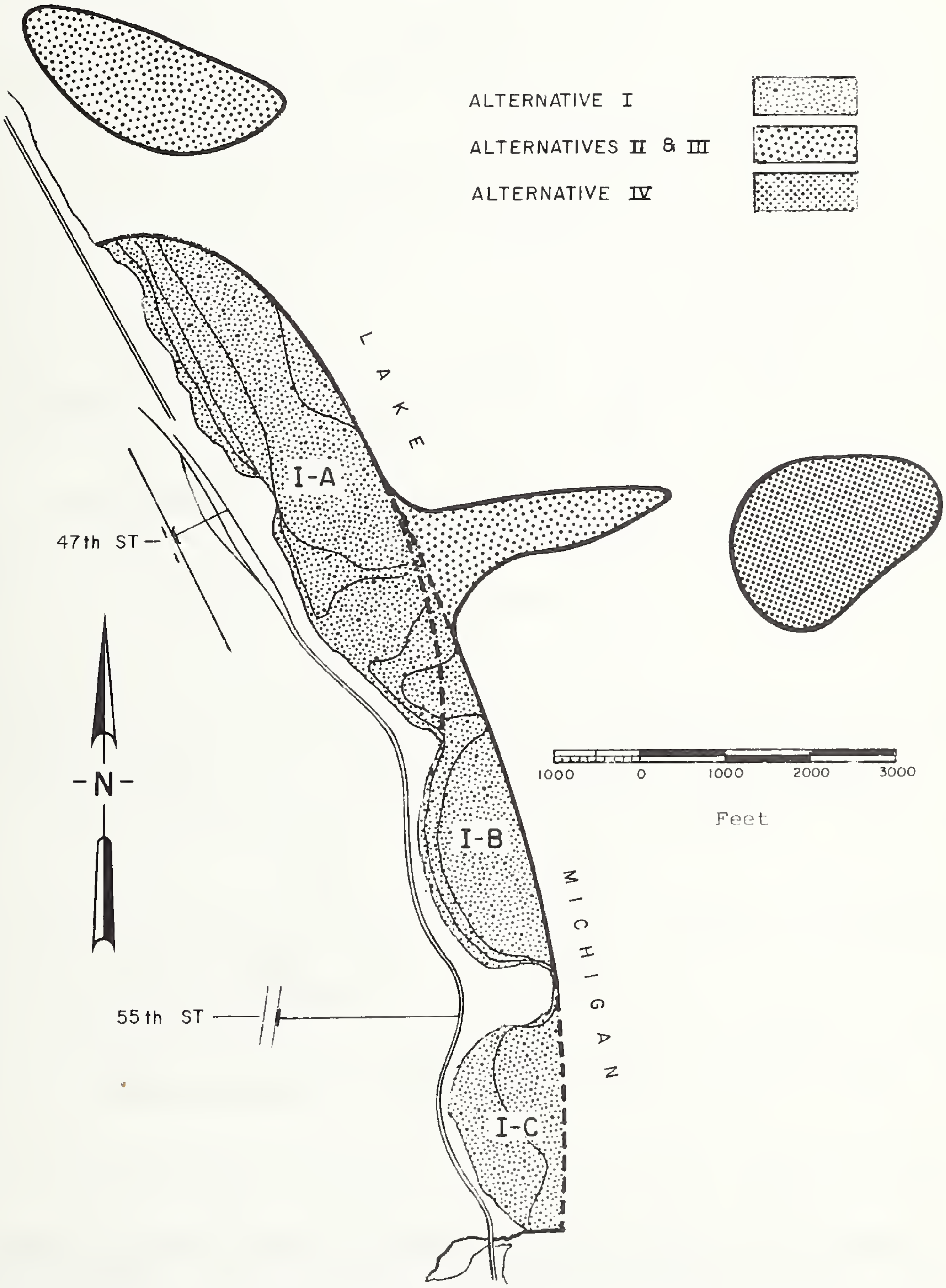
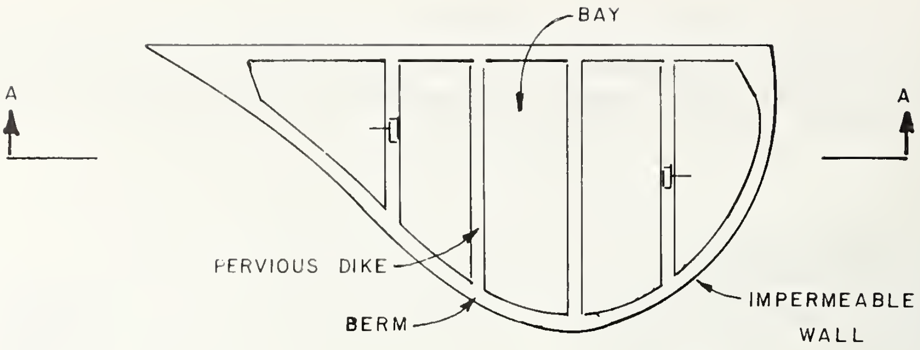
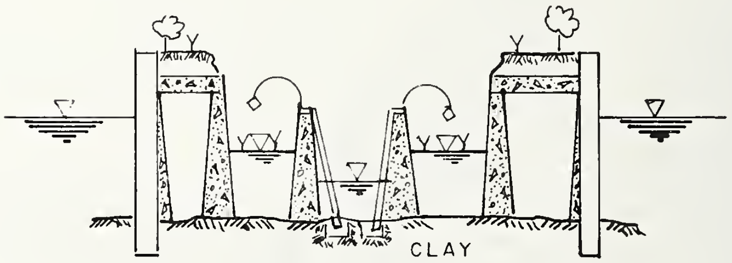


FIGURE 10-2. DETAILED LANDFILL PLAN FOR SOUTH SECTOR [10-1]

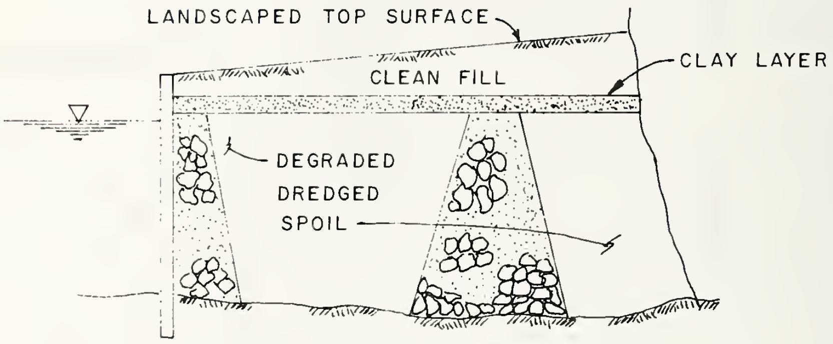
SOURCE: KBS: Exhibit 4



(A) AT DISPOSAL SITE



(B) CROSS SECTION A-A



(C) TREATMENT COMPLETED

FIGURE 10-3. BIOLOGICAL TREATMENT FOR DREDGE SPOIL MATERIAL [10-1]
SOURCE: KBS; Exhibit 9

The costs for disposal at the sector areas were then compared with standard disposal costs, such as trucking to the airport or other private landfill areas. The bar graph shown in Figure 10-4 illustrates which projects would save money by utilizing the "Central Sector" landfill site.

10.2.7.2 Alternative Muck Utilization Plans

In response to the lakefront land development program, various organizations proposed alternative utilization schemes.

The deep tunnel project planned by the Metropolitan Sanitary District of Greater Chicago (MSDGC) will produce the greatest volume of excavated material. This organization would receive the greatest benefit from a large scale landfill program. Other utilization schemes proposed by the MSDGC include stockpiling of blasted rock in old abandoned quarries for later use in aggregate production. This scheme would prevent the flooding effect of large quantities of aggregate and would permit long range use of the blasted rock. Also the rock muck could be used to develop ski slopes and other recreational type areas at completed sanitary landfill sites.

The CUTD transit system is also considering construction of ski mountains as an efficient utilization of spoil material. Both organizations are continuing their search for alternative economical disposal sites for spoil material.

10.2.8 Utilization Restrictions and Difficulties

The magnitude of the proposed lakefront land development program requires the participation of many public and private agencies. During the planning phase, the following key agencies were identified:

a. City of Chicago Department of Development and Planning-coordinating agency.

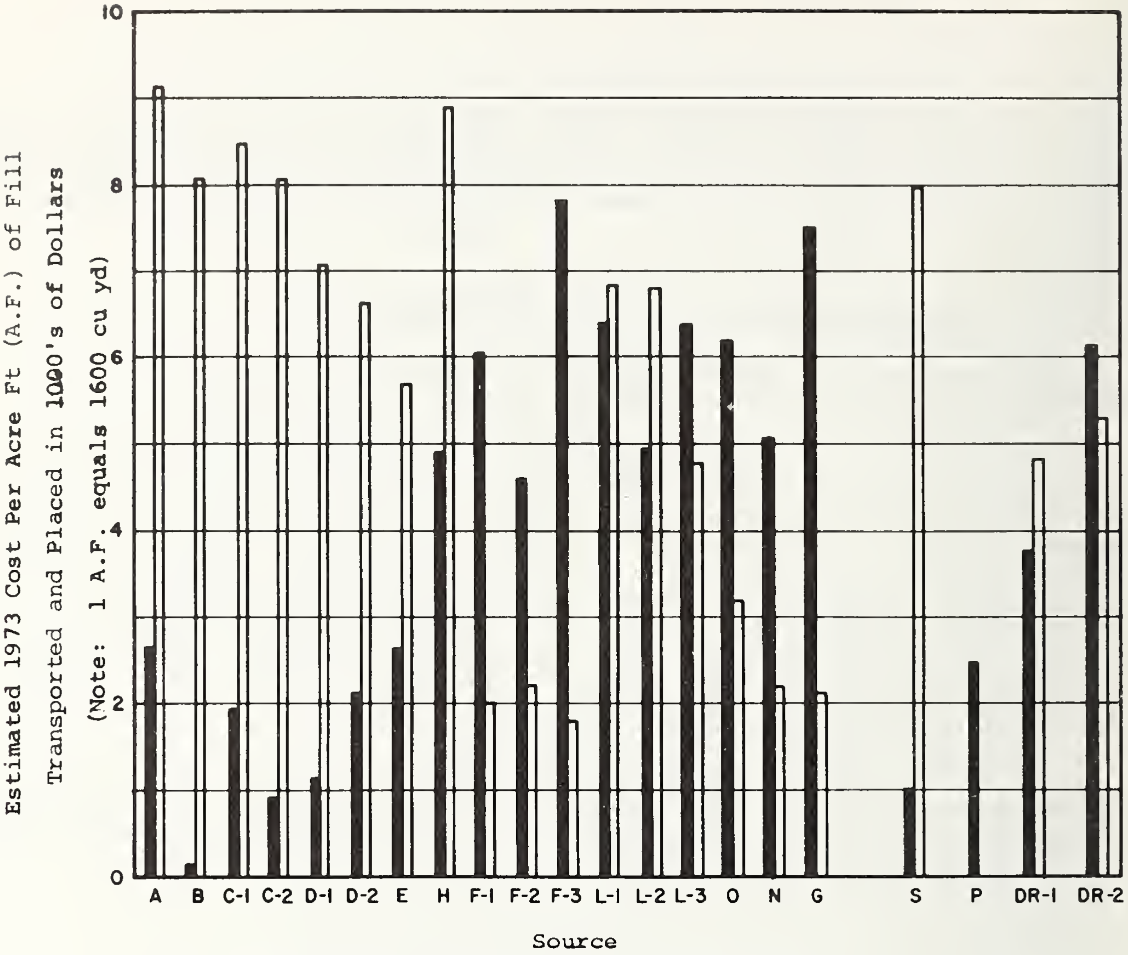
b. Chicago Park District - alternative coordinating agency. (In the past the Park District had been responsible for all lakefront land development programs.)

c. Metropolitan Sanitary District of Greater Chicago - potential source of spoil material.

d. Chicago Urban Transit District - potential source of spoil material.

e. U.S. Army Corps of Engineers - potential source of spoil material.

f. State of Illinois DOT, Division of Water Resources Management - jurisdictional authority over all public waters in Illinois.



TUNNEL AND RESERVOIR PROJECT
MAINSTREAM TUNNEL SYSTEM

A	Wilmette to Lawrence Ave.-697 A.F.
B	Chicago River Lateral - 93 A.F.
C-1	Lawrence Ave. to North Ave. -1401 A.F.
C-2	North Ave. to Chicago River - 551 A.F.
D-1	Chicago River to Damen Ave.-1082 A.F.
D-2	Damen Ave. to Central Pk. Ave.-582 A.F.
E	Central Pk. Ave. to Terminus - 2231 A.F.
H	North Branch Chicago River Lateral - 660 A.F.

CALUMET TUNNEL SYSTEM

F-1	Cal-Sag - Cicero Ave. to State Line - 976 A.F.
F-2	Cal. River - L Michigan to 138th St. - 976 A.F.
F-3	Little Cal. River - 138th St. to State Line - 967 A.F.

DES PLAINES TUNNEL SYSTEM

L-1	North Terminus to Belmont Ave. - 166 A.F.
L-2	Belmont Ave. to Cermak Rd. - 1022 A.F.
L-3	Cermak Rd. to South Terminus - 1041 A.F.

RESERVOIRS

O	Terminal - 53,925 A.F.
N	Calumet - 40,100 A.F.
G	Riverdale - 5,393 A.F.

OTHER SOURCES

S	Chi. Central Area Transit Proj. - 1680 A.F.
P	Local Dredging of Lake Bottom for Fill
DR-1	Calumet Harbor Dredgings - See Text
DR-2	Chicago River & Harbor Dredgings - See Text

LEGEND

COST FROM SOURCE TO SECTOR ALT.	ALTERNATE DISPOSAL

FIGURE 10-4. COST ESTIMATES FOR CENTRAL SECTOR: HARBOR AREA [10-1]
SOURCE: KBS; Exhibit 16

Coordination between agencies is essential. The entire landfill program is dependent upon the timely availability of spoil materials from the various construction projects. Since most of the proposed projects will be Federally subsidized, the construction schedules depend on funding grants. A delay of funds for any one project or part of the project may put the entire landfill program in jeopardy. For example, if the shot rock required for construction of protective barriers is not available prior to the delivery of the landfill materials, then the rock fill will have to be purchased from a quarry.

The Chicago Urban Transit District (CUTD), in a critical response to the land development program, indicated that disposal of material at the Central Sector would be most economical provided the protective barrier was constructed from the tunnel and reservoir rock spoil l [10-2]. If this rock fill were not available, a more economical disposal site could be found by CUTD outside the limits of the lakefront land development. At the time of construction, CUTD plans to choose the most economical disposal site. No prior commitments would be made.

It was found, in general, that long-range muck disposal planning has not been completed by the various contributing agencies. Moreover, each agency prefers to study its disposal needs at the time of construction. The lack of long-range planning and cooperation is a serious problem which must be solved by CCDDP.

Some of the communication difficulties affecting planning phases are evident in the CCDDP's reply to CUTD [10-4]. In its defense of the lakefront land development program CCDDP stated that:

a. Rock spoil from the tunnel and reservoir project will be available for protective breakwater construction.

b. The CUTD approach fails to consider a joint utilization program with other parties.

c. The alternative transit tunnel disposal site will not be available to the transit authority.

d. Both CUTD and CCDDP computed costs for disposal at the lakefront site but the unit costs were significantly different because different disposal methods were used.

The differences of opinion reflect the need for coordination and communication.

Public acceptance of the lakefront project is also a critical planning factor. Environmental groups are very concerned about the disposal of polluted harbor sediments. Other problems relate to the choice of truck routes and noise and dust created by the construction. In order to avoid unnecessary delays, the public must be properly informed and permitted to assist in the planning process.

The planning process was assessed by CCDDP and a checklist was prepared including 19 functional steps. Development of preliminary plans, approval by the City Mayor, detailed data collection and engineering studies, public relations, and preparation of contract and legal documents are some of the work items. A complete list is included in Appendix B.

10.2.9 Conclusions

a. The City of Chicago Department of Development and Planning (CCDDP) has promoted an extensive planning effort to utilize large quantities of rock and soft ground muck from proposed deep tunnels and subway construction.

b. It was determined by the CCDDP that the most useful and economical utilization of excavated materials over an extended period of time would involve the development of lakefront land areas.

c. Based on the decision in (b) above, a comprehensive study was completed to develop land forms and associated construction techniques for optimum utilization of the anticipated materials.

d. A project implementation checklist was prepared for completing the lakefront program.

10.3 NO. 2 - ATLANTA, GEORGIA

10.3.1 General

In 1965, the Georgia General Assembly created a mass transit agency, the Metropolitan Atlanta Rapid Transit Agency (MARTA) to develop mass transit plans for the City of Atlanta and the surrounding counties. This authority was granted the power to plan, design, construct, and operate a rapid transit system within the metropolitan area of Atlanta. Local county governments of Fulton, Dekalb, Gwinnet, Clayton, and the City of Atlanta voted to participate in the initial design phase of the project. The Board of Directors of the MARTA organization then consisted of members appointed by the participating local governments. An organizational framework chart for the MARTA organization is included as Figure 10-5. As a result of a November 1971 referendum, the counties of Gwinnett and Clayton declined to participate in the sales tax revenue program but have maintained representation on the board.

Parsons-Brinkerhoff-Tudor-Bechtel (PBTB) was initially retained by MARTA to serve as the general engineering consultant.

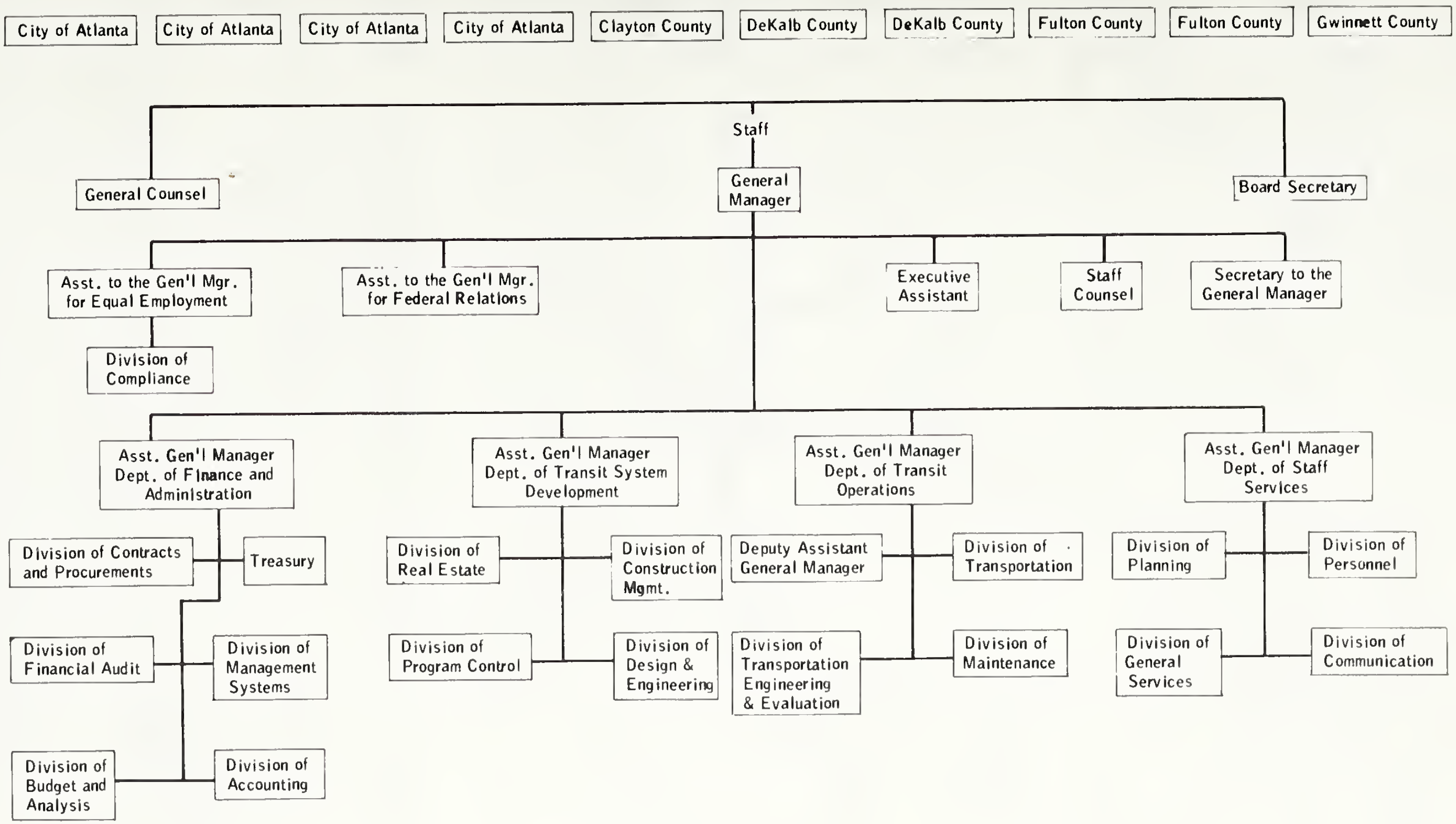

City of Atlanta
City of Atlanta
City of Atlanta
City of Atlanta
Clayton County
DeKalb County
DeKalb County
Fulton County
Fulton County
Gwinnett County
Staff
General Counsel
General Manager
Board Secretary
Asst. to the Gen'l Mgr. for Equal Employment
Asst. to the Gen'l Mgr. for Federal Relations
Executive Assistant
Staff Counsel
Secretary to the General Manager
Division of Compliance
Asst. Gen'l Manager Dept. of Finance and Administration
Asst. Gen'l Manager Dept. of Transit System Development
Asst. Gen'l Manager Dept. of Transit Operations
Asst. Gen'l Manager Dept. of Staff Services
Division of Contracts and Procurements
Treasury
Division of Financial Audit
Division of Management Systems
Division of Budget and Analysis
Division of Accounting
Division of Real Estate
Division of Construction Mgmt.
Division of Program Control
Division of Design & Engineering
Deputy Assistant General Manager
Division of Transportation
Division of Transportation Engineering & Evaluation
Division of Maintenance
Division of Planning
Division of Personnel
Division of General Services
Division of Communication

FIGURE 10-5. ORGANIZATIONAL FRAMEWORK FOR METROPOLITAN ATLANTA RAPID TRANSIT AUTHORITY

SOURCE: PBTB

10.3.2 Summary

Prior to 1975, MARTA's major effort was directed towards completion of the design for the eastline and westline routes. While no major construction contracts have yet been awarded, several smaller grading contracts for station areas are in progress.

A final environmental impact statement for the Metropolitan Atlanta Rapid Transit System was filed in May 1973 [10-5]. The statement covered the construction of the total 50 mile system as proposed by MARTA. Sections of this report described the problems of solid waste management, particularly the problems of disposal of excavated materials and debris from construction activities. Preliminary estimates indicate that about 2.26 million cu yd of demolition material will have to be wasted. Another 7 million cu yd of earth materials will be excavated. About 1.7 million cu yd of this material will be re-used in construction; the remainder is scheduled for disposal.

Based on other local construction activity, it appears that the urban development needs in the Atlanta area will provide a market for this excess excavation material. The irregular topography in the Atlanta area requires fill material in order to create level building sites. At least during the first phases of construction, Atlanta will be in a unique position: disposal sites will be very close to the actual construction areas, and costs for disposal will be partly offset by the sale of material.

10.3.3 Project Description

The overall system involves rapid transit by rail and the development of existing busway lines, plus the establishment of several new express busway lines. Service will be provided from outlying communities to the downtown central hub area of Atlanta referred to as Five Points Station. The proposed service routes and the construction sequence are shown in Figure 10-6. The initial work will be concentrated on the development of the east-west transit line including branches to Proctor Creek.

The rail line section of the system will comprise 56.2 miles of dual track rapid rail transit plus 40 stations [10-6]. A summary of the system components is given below:

Aerial Structure: 19.8 miles of rail and 11 stations

Grade Structure: 27.6 miles and 19 stations

Subway Structure: 8.8 miles and 10 stations

Major subway construction is limited to the downtown area. Aerial and surface grade systems will be used in the suburbs as shown in Figure 10-7.

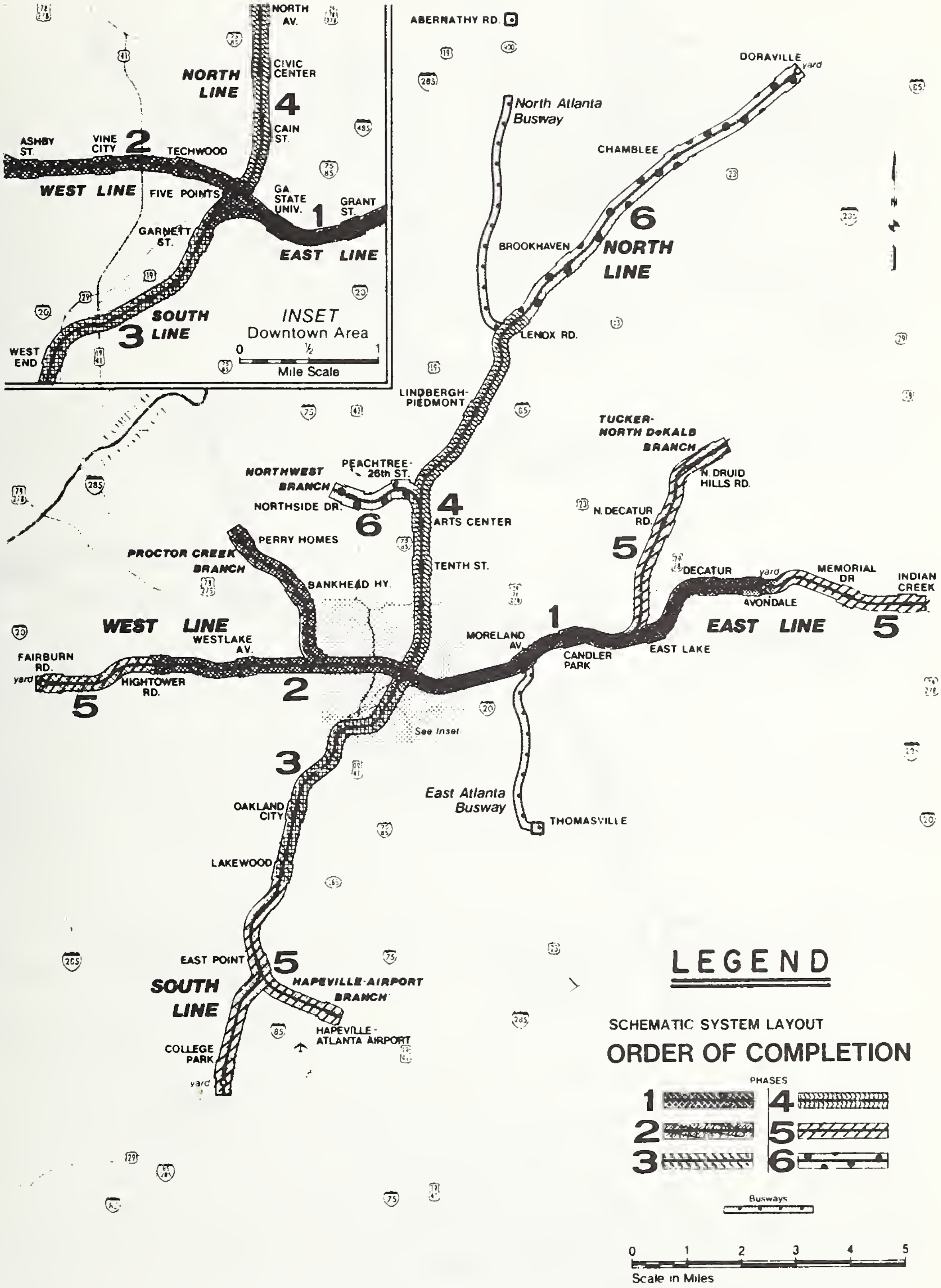


FIGURE 10-6. ATLANTA RAPID TRANSIT SYSTEM: ORDER OF COMPLETION [10-7]

SOURCE: PBTB

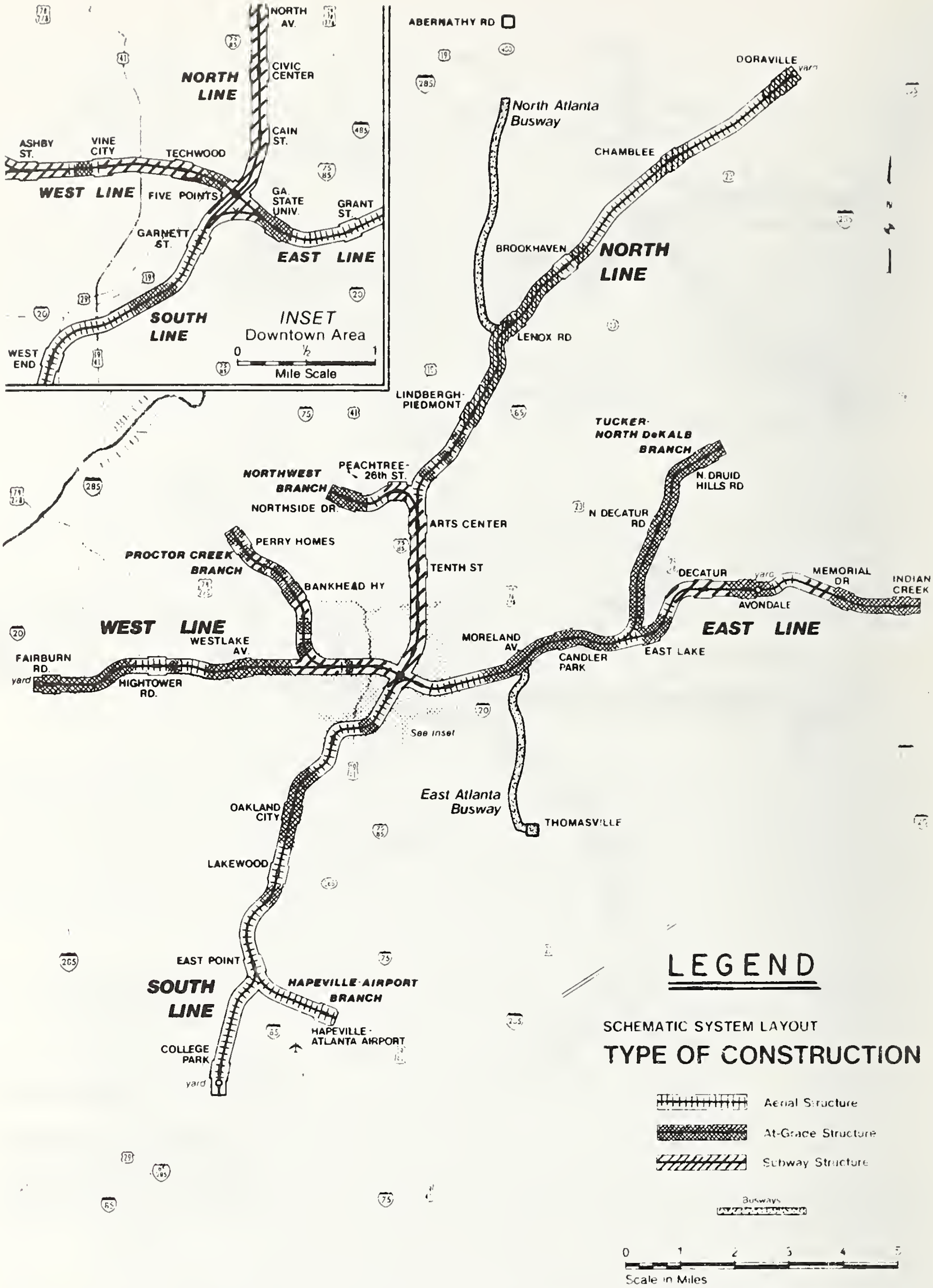


FIGURE 10-7. ATLANTA RAPID TRANSIT SYSTEM: TYPE OF CONSTRUCTION [10-7]

SOURCE: PBTB

The design and construction schedule for the system depends on many factors including revenue sales tax plan, funding, transportation needs, and population growth. The current project master schedule calls for completion of all design and construction activities by early 1980. A breakdown of the construction sequence for each of the major routes is shown in Figure 10-8. In order to meet this schedule, the final design for the entire system has been broken down into individual design packages involving short sections of each transit line. The final design for each of these sections or station facilities will be accomplished by individual design groups. To date, the general engineering consultant, PBTB, has selected 18 design teams involving more than 60 firms in order to meet the design and construction schedule.

A document entitled "Bidder Information Pamphlet," was prepared by PBTB to indicate the planned schedule of construction activity. According to that document, portions of the east and west line involving subway and aerial structure construction will be advertised in the first quarter of 1975 [10-6].

10.3.4 Geology and Subsurface Conditions

The topography around Atlanta is very irregular, with many swales and local depression. Typical surface profiles along the major routes have been prepared and are shown as Figures 10-9 to 10-13. During the preliminary design stage, test borings were completed along the proposed route in order to determine subsurface conditions.

In general, the soil conditions around Atlanta consist of residual soils and rock. The red "Atlanta Clay" is normally only a thin surface deposit which is usually removed prior to any building construction. The underlying residual soils are typically classified as sandy soil containing fractions of both silt and clay. For construction purposes, these sandy soils behave more like silts.

The rock in the area is generally metamorphic deposits of granite, gneiss and schist. The rock outcrops are normally much harder than the same materials which outcrop in the Washington DC area; however, the quality and hardness of the deposits do vary locally.

10.3.5 Method of Construction

The MARTA system will be divided into three major types of transit: (1) aerial, (2) at-grade, and (3) subway. The subway portions will be constructed by cut and cover or tunneling methods. Typical examples of each style of construction are illustrated in Figures 10-14, 10-15, and 10-16. Construction of the aerial line will involve little or no excess excavated materials. Construction of the at-grade line will involve a minimum of excess fill materials since the line is designed as a balanced cut and fill operation. Subway construction will be the primary source of excavated materials.

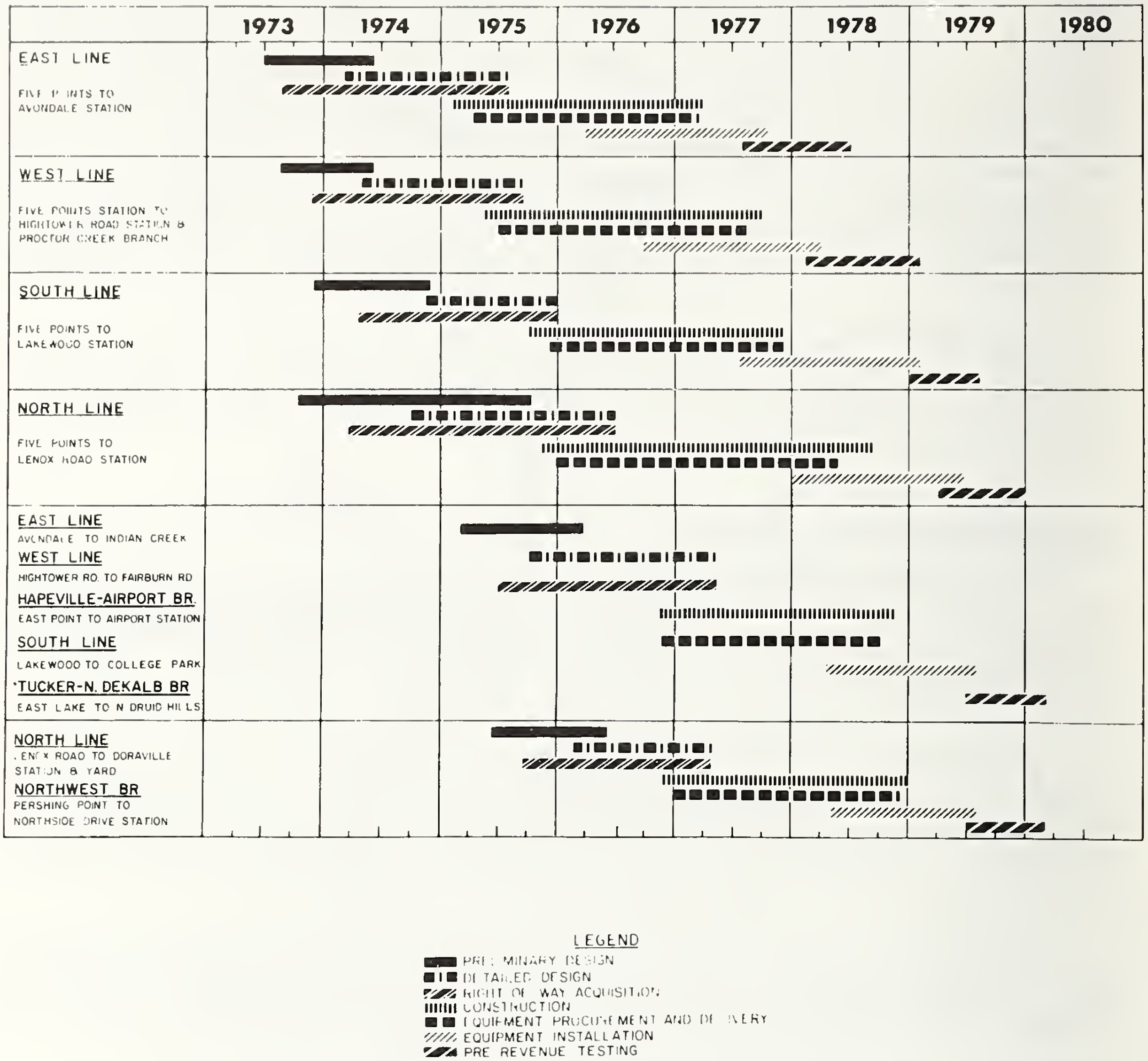


FIGURE 10-8. CONSTRUCTION SCHEDULE [10-7]

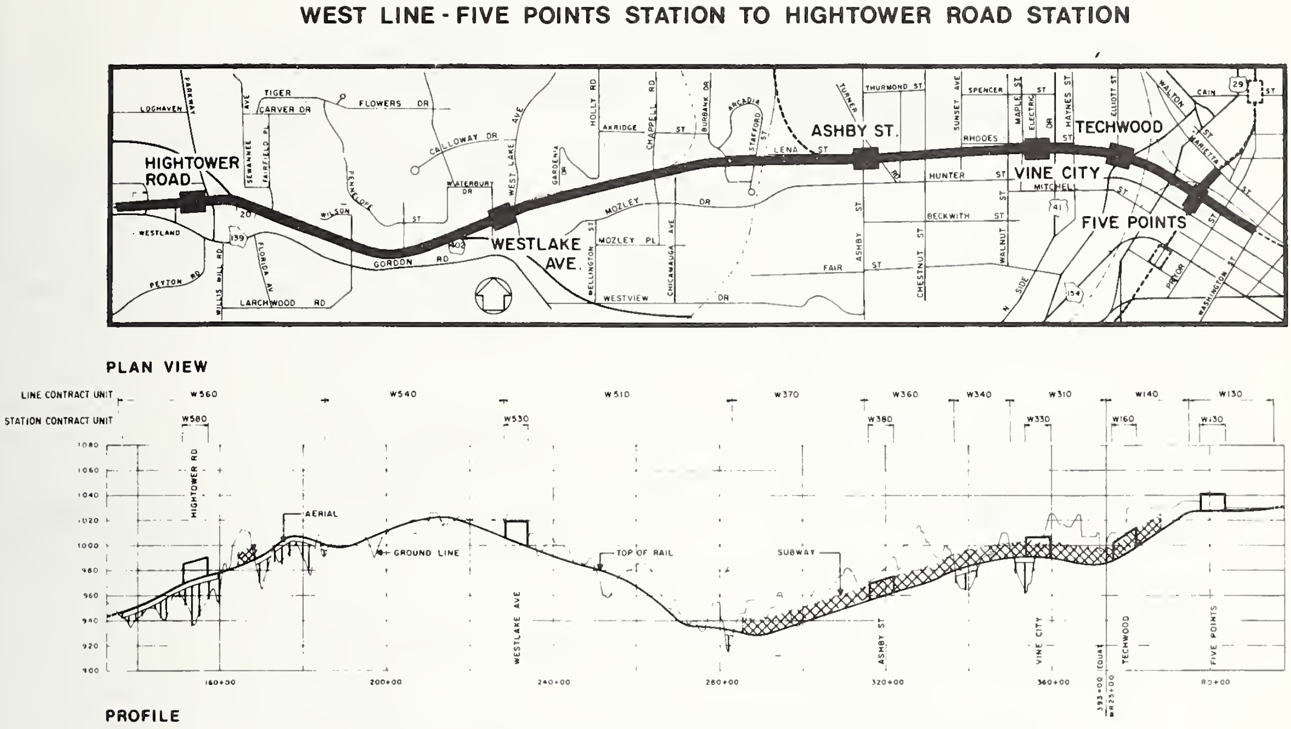


FIGURE 10-9. TYPICAL PROFILE - WEST LINE [10-6]

SOURCE: PBTB; p. iii

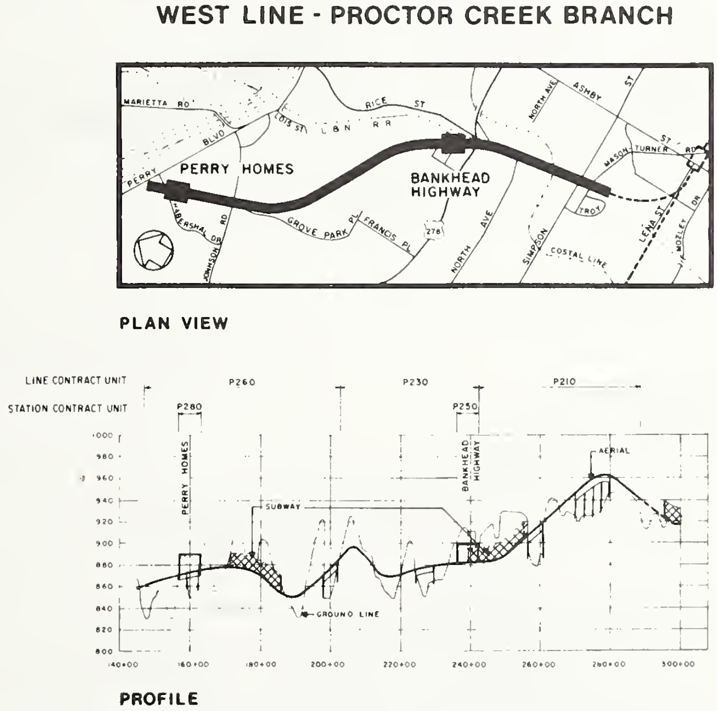


FIGURE 10-10. TYPICAL PROFILE - PROCTOR CREEK BRANCH [10-6]

SOURCE: PBTB; p. iv

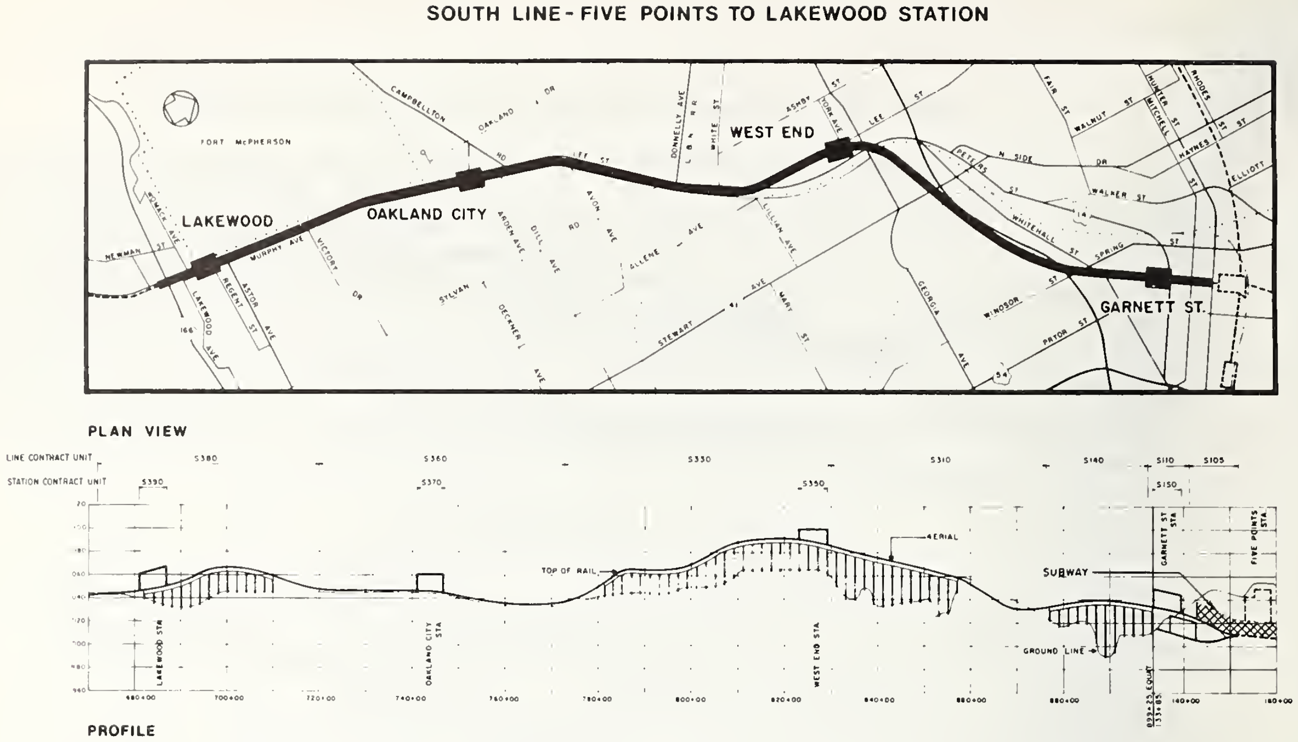


FIGURE 10-11. TYPICAL PROFILE - SOUTH LINE [10-6]

SOURCE: PBTB; p. v

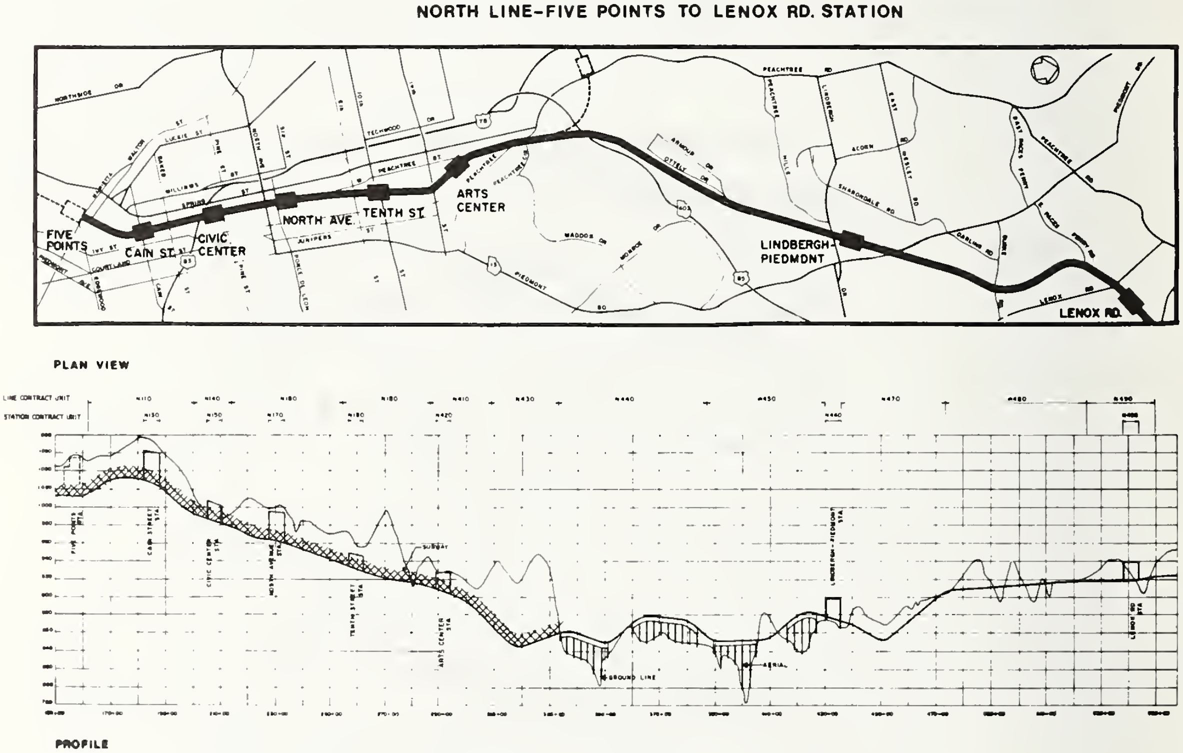


FIGURE 10-12. TYPICAL PROFILE - NORTH LINE [10-6]

SOURCE: PBTB; p. vi

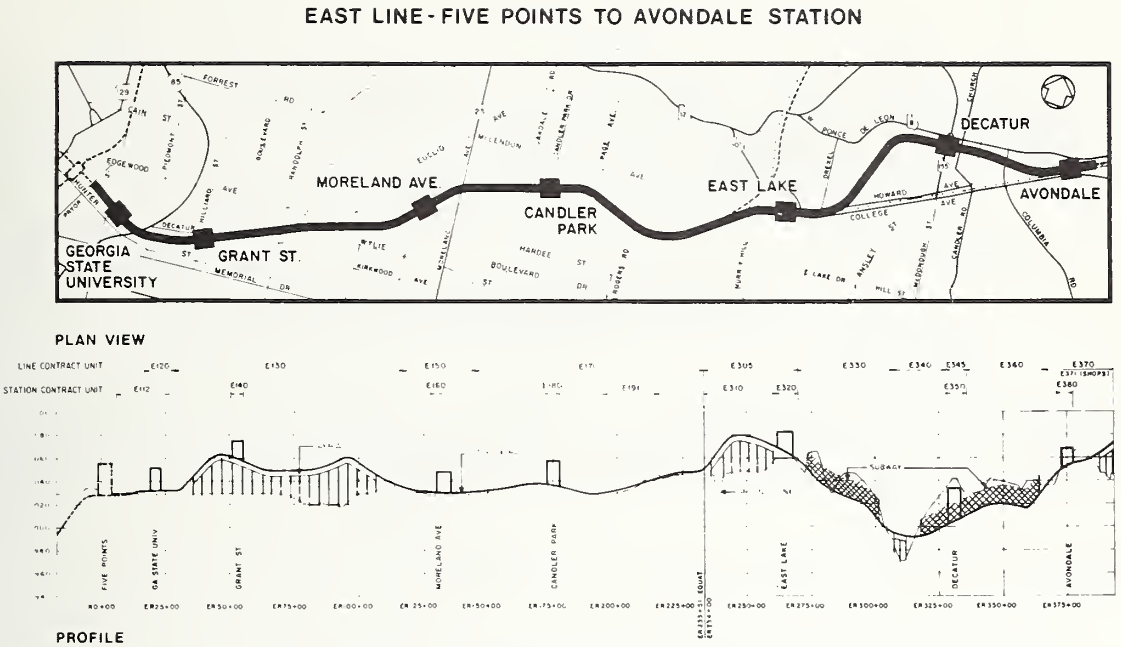


FIGURE 10-13. TYPICAL PROFILE - EAST LINE [10-6]
SOURCE: PBTB; p. ii

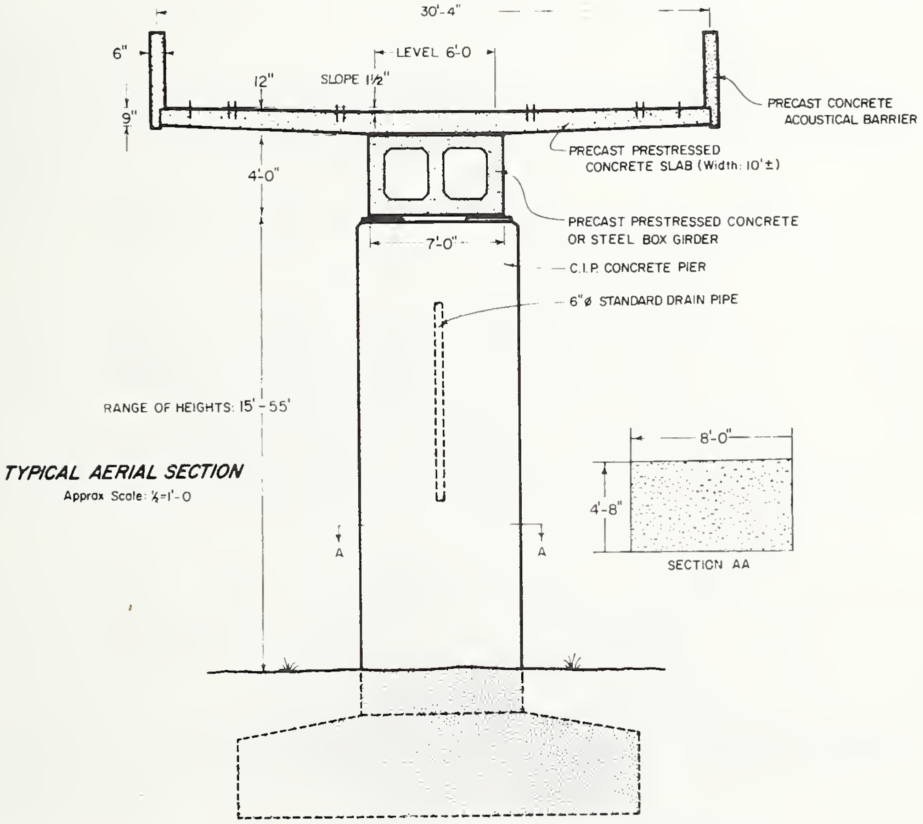

30'-4"
6"
LEVEL 6'-0
12"
SLOPE 1½"
9"
PRECAST CONCRETE ACOUSTICAL BARRIER
PRECAST PRESTRESSED CONCRETE SLAB (Width: 10'±)
4'-0"
PRECAST PRESTRESSED CONCRETE OR STEEL BOX GIRDER
7'-0"
C.I.P. CONCRETE PIER
6"ø STANDARD DRAIN PIPE
RANGE OF HEIGHTS: 15' - 55'
TYPICAL AERIAL SECTION
Approx Scale: ¼=1'-0
8'-0"
4'-8"
A
A
SECTION AA

FIGURE 10-14. TYPICAL AERIAL SECTION [10-6]
SOURCE: PBTB; p. xi

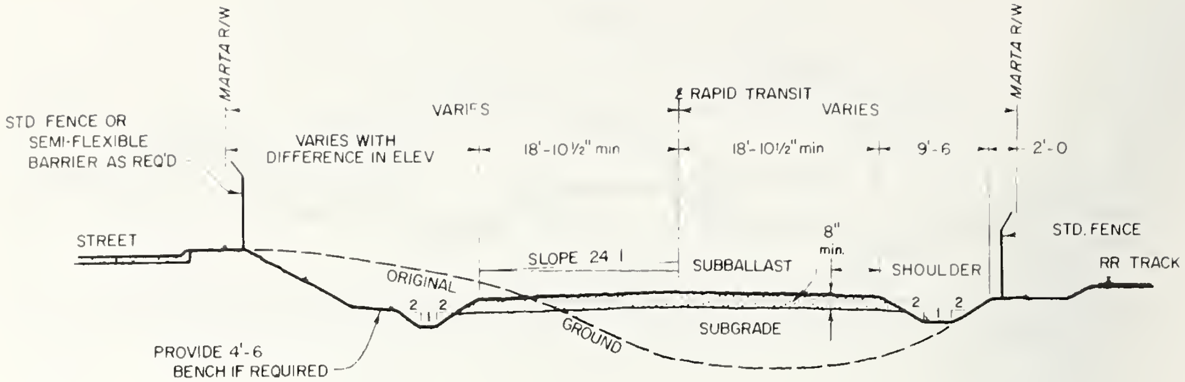


FIGURE 10-15. TYPICAL AT-GRADE SECTION [10-6]
SOURCE: PBTB; p. x

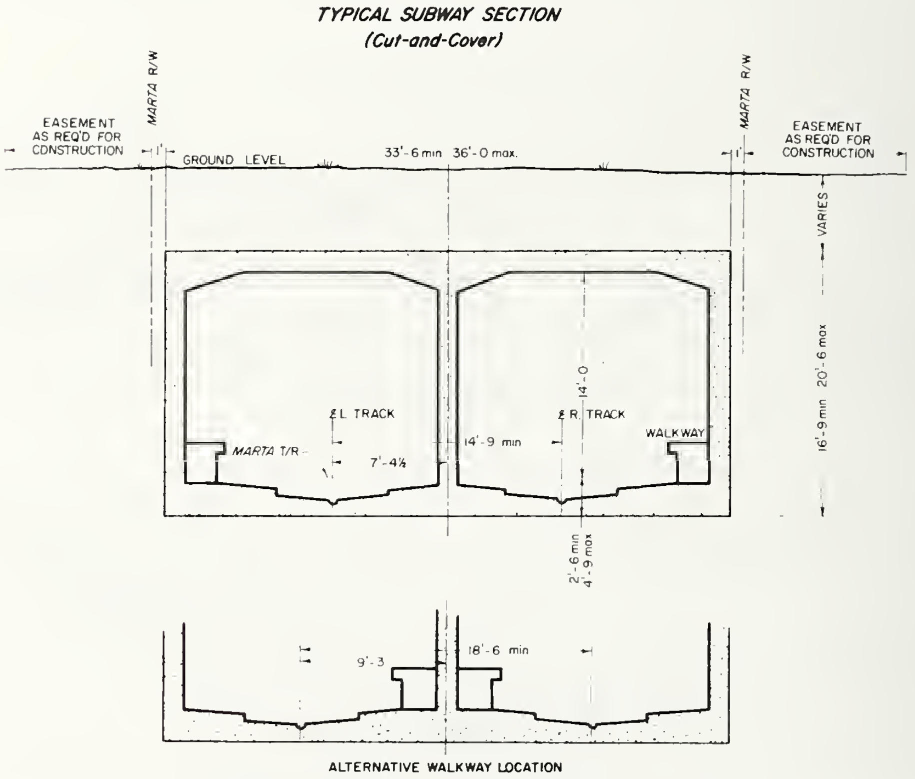


FIGURE 10-16. TYPICAL SUBWAY SECTION - CUT AND COVER [10-6]
SOURCE: PBTB; p. xii

At the present time, major design efforts are concentrated on the east-west line where a minimum of tunneling will be required. Furthermore, most of the downtown area subway work will not be initiated until 1976 [10-6]. The major area of rock tunneling will occur in the downtown Atlanta area along Peachtree Street. Along this stretch the subsurface profile consists of approximately 10 to 15 ft of soil overlying bedrock.

10.3.6 Types of Muck

Three general types of muck or excavated materials will be produced from the MARTA construction: (1) demolition debris, (2) earth excavated materials, and (3) rock excavated materials. These excavated materials will be produced from two general classes of construction:

a. Solid waste generated by demolition or land taking within rapid transit right of way.

b. Solid waste generated by construction of the rapid transit system.

The demolition waste and debris will consist of such materials as brick, wood, glass, aluminum, stone, and metal. A preliminary analysis of the number of structures which had to be removed from the right of way indicated that a total of about 3.16 million cu yd of debris would be produced. It is estimated that about 30 percent of this material will be recoverable for other uses. A breakdown of the quantity of debris to be produced from each line is shown in Table 10-3. The non-recoverable waste, amounting to about 2.3 million cu yd, is scheduled for disposal in the Atlanta area at various landfills or other approved disposal sites such as abandoned quarries.

The soil and rock materials to be removed during construction of the subway, aerial, and at-grade structures amount to approximately 7 million cu yd. It is estimated that 25 percent, or 1.75 million cu yd of this material will be suitable for backfill. This material will be utilized as part of the 4.5 million cu yd of backfill material required for (1) construction of railroad embankments, (2) backfill around at-grade structures, and (3) general site grading for parking and yard areas. The remaining 5.25 million cu yd of excavated soil and rock will require disposal outside the MARTA right of way.

All estimates of muck quantities are preliminary because each of the design teams has the privilege of changing grades from the original master plan prepared by PBTB. Thus the actual quantities of fill or surplus excavated material cannot be determined until the final design for each section has been prepared and submitted. These quantities are currently under study and in particular the quantity of debris materials is being carefully analyzed in order to establish environmental impact.

TABLE 10-3. QUANTITIES OF DEMOLITION WASTE MATERIAL WITHIN MARTHA'S RIGHT OF WAY [10-5]

SOURCE: UMTA

Section of Transit Line	Quantity of Waste Material, Cu Yd		
	Total	Recoverable	Waste
Central	390,000	123,000	267,000
East	920,000	187,000	733,000
South	562,000	185,000	377,000
West	623,000	165,000	458,000
Northeast	491,000	170,000	321,000
Northwest	29,000	9,000	20,000
Southwest	15,000	9,000	6,000
Tucker-North Dekalb	66,000	26,000	40,000
Proctor Creek	61,000	23,000	38,000
TOTALS	3,157,000	897,000	2,260,000

10.3.7 Contract Documents

A standard set of General and Technical specifications has been prepared for use in coordinating construction activities [10-7]. The technical specifications cover items such as site preparation, construction of embankments and drainage facilities, cut and cover excavation for stations, concrete aggregate, and other civil work items. The general provisions cover the legal and contractual items such as bidding requirements, scope of work, control of materials, and legal responsibilities. Supplemental specifications will be prepared as required in order to control the many construction contracts.

A review of the specifications with regard to disposal of muck and excavated materials indicated the following significant factors:

a. In several sections the specifications require that soil materials taken from excavations should be re-used as backfill unless the engineer determines the material unsatisfactory.

b. When surplus or unsuitable materials are produced from excavation work, the contractor must find his own method for disposal of the materials outside the MARTA right of way.

c. During construction, the contractor is required to control erosion, pollution of streams, noise, and dust in accordance with local, state, or Federal requirements, whichever is the most restrictive. Control over erosion, dust, and other potential pollution problems is covered in the general provisions (Section A7) and is reinforced in the technical provisions.

The re-use of excavated materials is most appropriate to the muck utlization concept. The general provisions (Section A6) state that the contractor may supply aggregate or borrow materials from any source, except when a mandatory source is designated in the supplemental specifications. The technical provisions (Section B3) further define six classes of embankment and subgrade materials which are used for structure backfilling, foundation backfill, and embankment construction. The materials must meet specification tolerances for gradation, volume change, and density, but the source is not restricted.

Unsatisfactory materials resulting from track excavation may be utilized to flatten the slopes of embankments or for other grading purposes. The engineer generally determines when material is unacceptable for construction. The specifications therefore emphasize the intent to utilize or save available excavated materials rather than automatically discard them as waste products.

10.3.8 Potential for Utilization of Excavated Materials

The initial construction effort will be concentrated on the east-west line where approximately 20 percent of the route length will involve tunneling or cut and cover construction. Thus the net overall surplus of excavated material will be small. Much of the route will be constructed at-grade where a balanced cut and fill design will utilize excavated materials as much as possible. Nevertheless, there are two specific instances where surplus excavated materials will be utilized as fill materials.

The Avondale Yard, located on the east line, will require fill materials to raise the grade of the car storage yard. It is anticipated that much of the fill will be obtained from adjacent subway contracts, particularly from the tunneling and station construction at the Decatur Station. Design of the yard area is not complete so that final quantities have not been established.

The Proctor Creek Branch splits from the west line at Washington Park. The line crosses the park as a depressed structure. To cover the structure and at the same time enlarge the park grounds, excavated materials from the adjacent tunneled section of the west line will be used to raise the park grade approximately 20 ft.

Further north on the Proctor Creek Branch, the line crosses an active rock quarry. An agreement has been reached between the quarry operator and MARTA such that the rock in the MARTA route will be excavated by the quarry operator prior to MARTA construction.

The irregular topography in the Atlanta area requires fill materials for site development. Based on past construction history, it is anticipated that the demand for fill will absorb any surplus excavated materials. In addition, there are several abandoned quarries which could be used as disposal sites.

Eventually the MARTA system will be expanded to service the Atlanta Airport as shown in Figure 10-6. The approach to the airport will be underground and construction will be accomplished by tunneling or cut and cover methods. In either case, excavated materials can be utilized at the extensive 3800 acre Atlanta airport [10-8]. In recent years, the facilities have been expanded and rough site grading has involved the placement of more than 15 million cu yd of fill. Final site grading could easily absorb several million cu yd of fill.

10.3.9 Utilization Restrictions or Difficulties

The problem of solid waste management was reviewed in the Final Environmental Impact Statement [10-5]. Solid waste disposal is regulated by the Georgia Department of Natural Resources and is subject to compliance with the following laws:

a. "Rules and Regulations for Solid Waste Collection and Disposal," Chapter 270-5-26 of the Georgia Code Annotated.

b. "Solid Waste Management Act 1486," Georgia Laws, 1972.

c. "Rules and Regulations Pursuant to Section 4A of Solid Waste Management Act of 1486," Georgia Laws, 1972 (when adopted).

These laws require that the contractor submit detailed plans for disposal of solid wastes which are safe, non-obtrusive, environmentally sound, and in accordance with applicable local, state and Federal regulations. During the final stages, PBTB will re-analyze and update the anticipated volumes of material to be produced from each contract section. These design quantities will be useful in appraising the overall solid waste disposal problem, but the Standard Specifications and the Georgia Laws will ultimately compel the contractor to take proper care of the disposal program.

In a technical or market place sense, there are likely to be few problems associated with actual disposal of materials from the MARTA construction. Access to some disposal sites such as county landfills may be restricted by local opposition. Opposition has already been voiced and, as a result, one landfill site will be closed to disposal of MARTA debris. Because of the refusal to commit sales tax funds for MARTA activities, Gewinnett and Clayton Counties may resist disposal of construction debris within their borders.

At the present time, no plans have been prepared for utilization of excavated materials from rock tunneling operations along the north line beneath Peachtree Street. Abandoned quarries, private development, and the airport are potential disposal sites. However, the anticipated high cost of trucking material 10 or 12 miles may eliminate the airport as a disposal site. It is possible that the rock muck might be utilized as track ballast, but additional studies would be required to confirm the rock quality.

The scheduling of the entire project is affected by Federal funding. In response to an initial request for $237 million for construction funds, only $80 million was granted [10-9]. MARTA has three options available: (1) extend the duration of the local sales tax, (2) issue more bonds, or (3) stretch out the construction schedule. At the present time no reduction in the scope of work is anticipated. The reduction in the level of funding could result in a change in construction contract scheduling and thus affect muck utilization plans. For example, an excavation contract may proceed, but delay of a fill contract would preclude the use of the surplus excavated material as backfill. Or a fill contract might not have the material available from a delayed excavation contract.

10.3.10 Conclusions

a. No immediate muck utilization and/or disposal problems exist in the Atlanta area. Demand for fill materials on private projects will absorb the surplus material produced by MARTA construction.

b. Disposal of demolition debris is regulated by state and local ordinances. Some resistance to the use of local landfills has developed, but MARTA engineers are studying the problem.

c. Project specifications generally require that all excavated materials acceptable to the engineer be re-used in the construction.

d. A decrease in the anticipated level of Federal funding may affect the entire project schedule. In turn, the changes in schedule may affect construction schedules and the ability for re-use of materials on adjacent projects.

10.4 NO. 3 - BALTIMORE, MARYLAND

10.4.1 General

The City of Baltimore is embarking on the construction of a totally new mass transit system (Baltimore Region Rapid Transit System--Phase 1). Principal organizations involved in the project are listed below:

Owner:	Mass Transit Administration (MTA) State of Maryland Department of Transportation
General Design Consultant:	Daniel, Mann, Johnson & Mendenhall/Kaiser Engineers (DMJM/KE)

10.4.2 Summary

The design work for some sections of the system has been completed; other sections are near completion. The first major construction contract was awarded in late fall of 1976. Work on one station entrance, a ground breaking contract, has already been completed.

A final Environmental Impact Statement (EIS) has been submitted and the overall transportation plan has been approved by all state and local government bodies [10-10]. The problem of muck disposal has been addressed in one section of the EIS entitled "Disposal of Material to be Excavated."

According to initial estimates, approximately 2 million cu yd of material will be produced from the approximately 4 miles of subway and cut and cover stations planned for Section A of Phase 1 [10-10]. Preliminary studies had indicated that excavated materials could be utilized as fill at the Baltimore-Washington International Airport and for development of harbor facilities for the Maryland Port Administration. Subsequent developments indicated that excavated materials might be utilized for parkland development and that utilization of large quantities of fill at the airport appeared unlikely.

In early 1976, the design effort in Baltimore had reached the state where utilization of tunnel muck could be achieved with a concentrated planning effort. At that time, Haley & Aldrich, Inc., working under an on-going contract with the U.S. Department of Transportation and with the consent of the MTA, undertook a study to develop and implement a muck utilization program for the proposed subway construction in Baltimore. The planning concepts described in this report were employed and a muck utilization plan (described hereinafter) was finalized for Phase 1, Section A. The plan is currently being incorporated into the project's contract documents by the MTA and their general consultant, DMJM/KE.

10.4.3 Project Description

Plans and construction activities for the City of Baltimore's rapid transit system are concentrated on the development of the northwest and south service corridors, identified as Phase 1.

Phase 1 will eventually require the construction of 28 miles of transit line in the following general proportions:

subway	9 miles
aerial structure	9 miles
ground level	10 miles

Twenty stations will also be built as part of Phase 1 construction. The approximate locations of the various types of construction are shown in Figure 10-17. Additional general information about the transit system is provided in Figure 10-18.

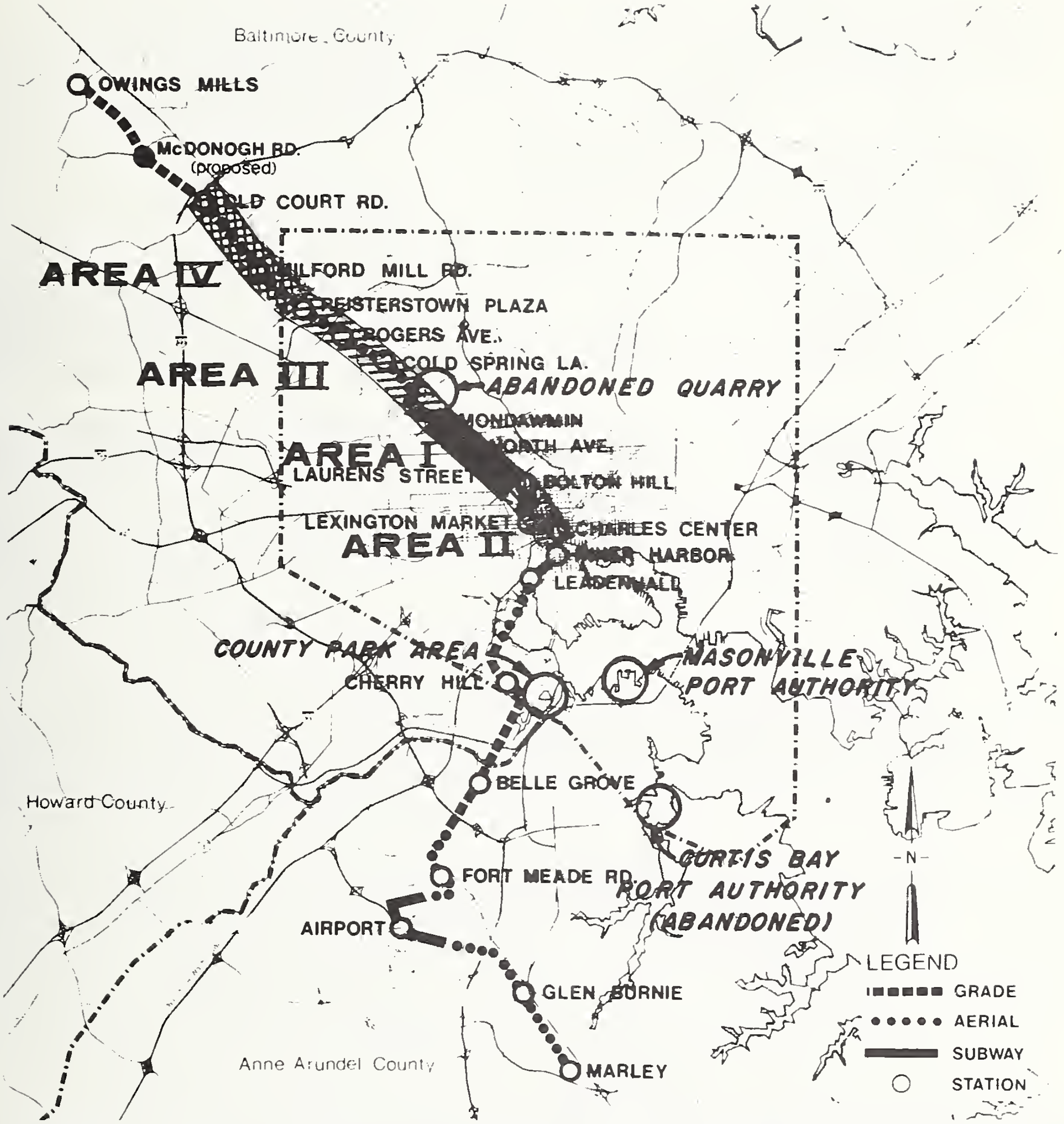


FIGURE 10-17. NORTHWEST AND SOUTH LINES FOR RAPID TRANSIT SYSTEM IN BALTIMORE [10-11]

SOURCE: MTA

ROUTE DESCRIPTION:

PHASE I — 28 MILES:

9 miles in .... subway
9 miles on .... aerial structures
10 miles on .... ground level

NORTHWEST LINE: Extends 14 miles between Owings Mills in Baltimore County to Charles Center in Baltimore City.

SOUTH LINE: Extends 14 miles between Charles Center to Baltimore/Washington Airport and Marley in the vicinity of Southdale in Anne Arundel County.

PHASE I STATIONS — 20:

Station Key: aerial (a), subway (s), on grade (g), with parking facilities (/p)

NORTHWEST LINE — 11

Owings Mills (g/p)
Old Court (g/p)
Milford Mill (g/p)
Reisterstown (a/p)
Rogers Ave (a/p)
Cold Spring Lane (a/p)
Mondawmin (s)
North Ave. (s)
Laurens (s)
Bolton Hill (s)
Lexington Market (s)

SOUTH LINE — 8

Inner Harbor (s)
Leadenhall (s)
Cherry Hill (a/p)
Belle Grove (a/p)
Fort Meade (a/p)
Airport (s)
Glen Burnie (a)
Marley (a/p)

CENTRAL STATION

Charles Center (s) — Downtown transfer terminal station between Northwest and South Lines.

STATION SERVICES:

Stations' areas are not limited to, but generally include:

Pedestrian access from parking lots Kiss and Ride zones and/or feeder bus stops.

Parking, where provided by design is anticipated to include both free parking and low cost meter parking.

Parking area controlled and maintained by the MTA.

Public access to station buildings as required by aerial, surface or subway design will offer weather protection, escalators, stairs and/or elevators to move patrons to the train platforms.

All station exteriors will be landscaped and aesthetically conform to neighborhood environs.

All route trackways will be safety protected from unauthorized entry.

Inside station building, public or free area, design features will include:

Public telephones
Security system
Ticket and change vending machines
Directional signing
Bus transfer machines
Information booths
Station attendants

Paid area of the station and train platform area is accessible to only those patrons using the train service.

Train platforms are to be designed as center platforms with trains operating on both sides and passenger boarding from center area for either direction.

SPECIAL FEATURES:

Baltimore's Rapid Transit System will be the third system in the U.S. to be constructed as a totally new system. Patronage on a daily basis will exceed 225,000 riders. All stations will be served by an extensive feeder MTA bus system. All stations will provide special handicapped provisions, i.e., elevators, handrails, texture surface materials, etc.

SERVICE CHARACTERISTICS:

Propulsion: Electric Motors
Average train speed — 40 mph
Maximum train speed — 75 mph
Average distance between stations 1.34 miles
Patron access to station by: MTA feeder bus
private vehicle
bicycles
walking

Automatic fare collection system
Automatic train controls with onboard attendant
Train service, 5:00 a.m. to 1:00 a.m. — 20 hour day

CONSTRUCTION:

Construction will begin in 1974 along the Section A 8.5 mile portion from the Inner Harbor Station northwest toward the Reisterstown Road Plaza Station. Barring unforeseen delays, an estimated completion date of Phase I is 1980. Funding for Phase I is provided by the State of Maryland through the Maryland Department of Transportation Consolidated Trust Fund and the U.S. Department of Transportation.
Present Federal participation of cost is approximately 80%.

VEHICLE DETAILS:

Rapid Transit Car — 75ft. long, 10ft. wide, 10ft. 10in. high.
Maximum Train Length — 6 cars — 450 ft. Vehicles to be designed as married pairs. Extensive acoustic refinement and air cushioning to enhance riding quality.

Exterior: Brushed aluminum or stainless steel finish. Permanently sealed tinted safety windows, eight windows per car side. Three sets double doors per side. Doors — approximately 50 in. wide, 6ft. 4 in. high when open.

Interior: Air conditioned, heat controlled, upholstered seating for 80, standing capacity for 80. Sound proofing, onboard communications, handholds.

FIGURE 10-18. SYSTEM INFORMATION SHEET [10-11]

SOURCE: MTA

Initial Phase 1 funding and construction activities are limited to an 8 mile portion of the route from an area just northwest of the Reisterstown Plaza Station to Charles Center Station. This part of the route, identified as Section A, consists of the following approximate breakdown of construction type:

subway	4 miles
aerial structure	3 miles
ground level	1 mile

In order to minimize disruption to the downtown Baltimore area, much of the route will be constructed as a tunnel. All stations will be cut and cover construction.

Charles Center Station will be the central hub of the system. An 80 ft deep braced excavation will be required to construct the five underground floor levels to provide a vertical grade separation between the north-south and east-west subway lines. All train platforms will be designed as center platforms with trains operating on each side and passengers boarding from the center area.

10.4.4 Geology

The geology of the Baltimore area with respect to rapid transit construction has been described in several reports prepared by Robert B. Balter, Soil and Foundation Consultants, Inc. [10-12]. The following discussion of general geologic conditions has been taken from this recent series of 1974 general reports.

The Baltimore city area is divided into two major topographic areas, the Coastal Plain and Piedmont Provinces. The boundary between the two areas is commonly described as the "fall line," a name derived from the turbulent flow in streams leading from the higher Piedmont deposits to the Coastal Plain area. Soil deposits in the Coastal Plain area normally consist of sand, gravel and clay. The Piedmont area is characterized by natural soil deposits formed by weathering of the underlying hard Pre-Cambrian rocks.

Bedrock in the area consists primarily of metamorphic schists and gneisses and intrusive igneous gabbros. From the upper to the lower deposits, the bedrock is identified as the Wissahickon formation, the Cockeysville marble, the Setters formation, and the Baltimore gneiss. All of these formations and rock types were deposited in the Pre-Cambrian Era.

During subsequent geological periods, portions of the Baltimore land area were raised above the sea and little or no sediments were deposited. Although glacial ice did not reach Baltimore during the Pleistocene Age, meltwater streams and rivers deposited sediments consisting primarily of sand and gravel. This sedimentation process has been continued to the present as rivers are continually depositing silt, sand and gravel in the delta areas.

Test borings were completed along the proposed transit route to identify the particular soil and rock to be encountered during construction. The following paragraphs summarize the anticipated soil and rock conditions along the Phase 1, Section A route. The Phase 1, Section A route has been divided into four "Areas" shown in Figure 10-17.

Area I - Includes Eutaw Place and Dolphin Street to the portal at the Western Maryland Railroad; (Sta. 71 + 00 to Sta. 228 + 00)

Area II - Includes Baltimore and Frederick Streets to Eutaw Place and Dolphin Street; (Northwest Line Sta. 0 + 00 to Sta. 71 + 00 and Northeast Line Sta. 0 + 00 to Sta. 17 + 00)

Area III - Includes the portal at the Western Maryland Railroad to the Baltimore City Limit; (Sta. 228 + 00 to Sta. 400 + 31)

Area IV - Includes the area from the Baltimore City County Line to the Baltimore Beltway Future Exit Number 19; (Sta. 794 + 75 to Sta. 664 + 00)

10.4.4.1 Area I

The transit route through this area will be tunneled, except for cut and cover construction at the portal and three station locations. Test borings indicate that materials which will be encountered include fill, natural sand and gravel, weathered rock, and sound igneous rock.

In the portal area (Sta. 221±) excavation will encounter fill materials consisting of a sandy silt with clay. Historical records show fill was placed in 1894. Along the remainder of the route the tunnel will encounter materials ranging from sound to weathered rock, sand and gravel, micacious clay, and fine sand. Station excavations will encounter fill overlying natural soil and weathered rock. The southerly sections of the route (Sta. 71 to 101) will encounter coarse sand and gravel.

10.4.4.2 Area II

This section involves construction of an underground transit route through downtown Baltimore. Both tunneling and cut and cover construction are contemplated. Soft ground tunneling methods will be required; open excavations will generally encounter a layer of fill overlying natural soil consisting of dense sand and gravel deposits with lenses of silt or clay.

10.4.4.3 Area III

Most of the route in this area will consist of an aerial structure; the remainder will have an at-grade design. Natural soils formed from weathering of the parent rock generally consist of coarse to fine sand and clayey silt overlying shallow bedrock. Rubble fill was found from Sta. 223 to 245.

10.4.4.4 Area IV

The transit line will be a surface line throughout this area. The line will require cut and cover sections of less than 20 ft vertical dimensions. Soil types generally consist of coarse to fine sand, sandy silt, and silty clay. These natural soils were formed by weathering of the parent bedrock.

10.4.5 Muck Utilization Study

The study undertaken by Haley & Aldrich, Inc., to develop a muck utilization plan for the proposed subway construction in Baltimore had several purposes: (1) attempt to minimize both the costs for disposal of excavated materials and supply of backfill materials for the MTA construction and (2) attempt to coordinate with other public, state, city, and county projects which might benefit from the use of excavated materials.

The scope of the study included:

a. Establishing a Muck Utilization Coordinating Committee and acquiring necessary data.

b. Developing muck utilization alternatives and selecting a muck utilization plan.

c. Preparing and reviewing specifications relative to muck utilization.

10.4.5.1 Muck Utilization Coordinating Committee

During the initial stages of the study, a coordinating committee, Muck Utilization Coordinating Committee (MUCC), of city, county, and state agencies was formed to review current and future construction projects. This provided an efficient means of establishing communication with the various planning agencies and initially identifying projects which might benefit from a utilization program.

MTA assumed the leadership role. The MUCC was chaired by Mr. Frank Hoppe, Director of Engineering and Construction. Haley & Aldrich, Inc., served in the capacity of advisors to the MUCC. The MUCC members were as follows:

Maryland State Agencies

a. Mass Transit Administration (MTA)

b. Maryland Port Administration

c. State Aviation Administration

d. State Department of Natural Resources

e. Interstate Division Baltimore City

General Consultant

a. Daniel, Mann, Johnson & Mendenhall/ Kaiser Engineers, General Consultant to MTA

Baltimore City

a. Bureau of Parks and Recreation

b. Bureau of Construction Management

c. Department of Public Works

d. Redevelopment Agency

Baltimore County

a. County organizations similar to those described for Baltimore City and represented by the County Department of Public Works

10.4.5.2 Muck Characteristics

Aproximately two million cu yd of material will be produced from the approximately four miles of subway and six cut and cover stations contemplated in Section A of Phase 1. Approximately 80 percent of the excavated materials will be earth; the remaining 20 percent will be rock. Figure 10-19 presents the anticipated volume flow diagram for these materials. The relative breakdown of the materials for each of the major construction contracts is shown in Table 10-4.

Laboratory soil tests have been performed on soil samples obtained during the test boring program [10-12]. Standard gradation tests conducted on these samples indicate that soft ground soils will range from gravelly coarse to fine sands containing less than 10 percent of material finer than a No. 200 mesh sieve to silty sands containing up to 40 percent finer than the No. 200 sieve. The variety and range in gradations must be expected due to the method of deposition of the sediments. The sands and gravels predominate; finer-grained soils generally occur as lenses and pockets within the granular mass.

Severely weathered to fresh igneous and metamorphic rock will be encountered along portions of the proposed construction.

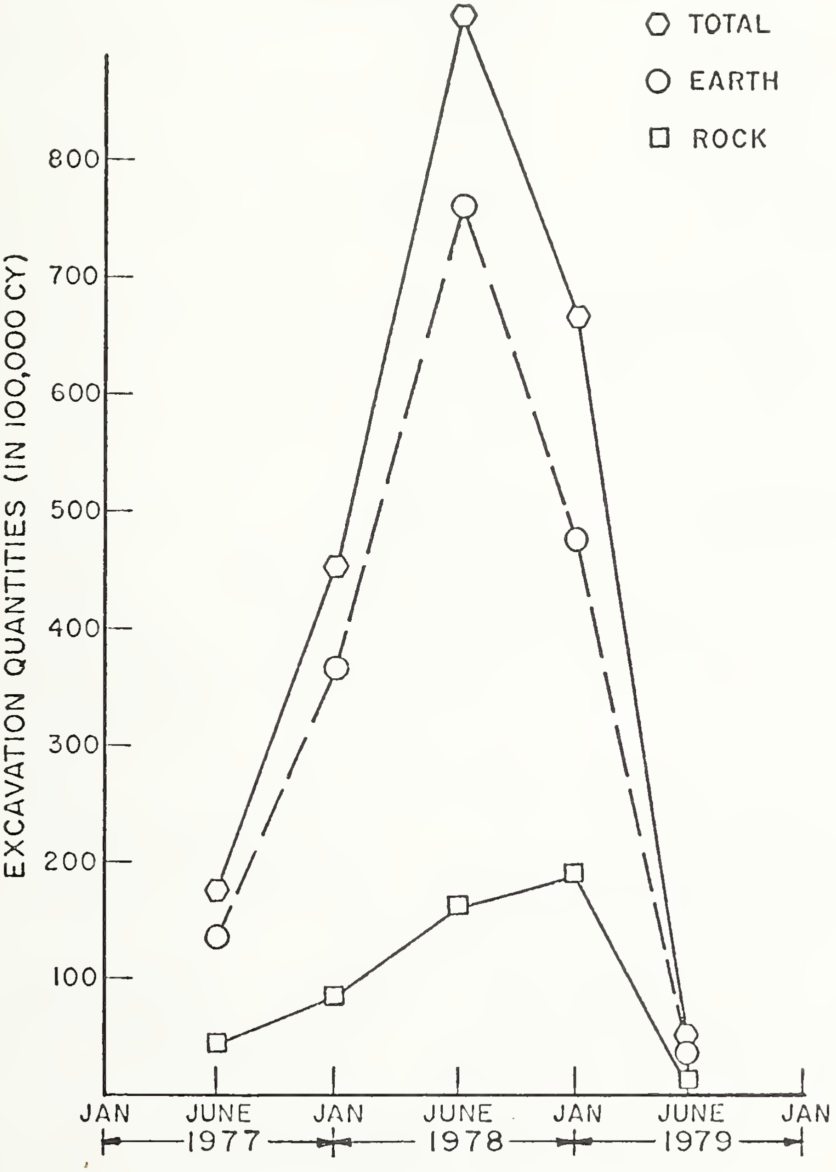


FIGURE 10-19. EXCAVATION QUANTITIES

TABLE 10-4. EXCAVATION AND BACKFILL QUANTITIES

	EXCAVATION (Cu. Yds.)		BACKFILL (Cu. Yds.)
	COMMON	ROCK	
Chas. Center Station	254,000		30,500
Lexington Market Tunnel	46,000		
Lexington Market Station	159,000		15,500
Bolton Hill Tunnel	218,000		
Bolton Hill Station	140,000		51,000
Laurens Station & Line	133,000	5,000	25,000
North Ave. Station & Line	70,000	113,000	15,000
Mondawmin Line	353,000	243,000	(230,000?)
Mondawmin Station	95,000	130,000	22,000
Coldspring Lane	15,000		6,000
Rogers/Reisterstown	303,000		33,000
	1,786,000	491,000	198,000*

*Excludes Mondawmin Line
(Cut & Cover Portal)

10.4.5.3 Investigation of Muck Utilization Alternatives

Four projects were ultimately identified as potential disposal sites in the utilization program. These are described in detail in the following section of this report.

Many other Baltimore city and county agencies were interviewed and current and proposed projects were investigated in an attempt to locate prime candidates for the utilization program. A summary of the projects and agencies investigated is included in Table 10-5.

Projects investigated included filling or supplying of cover materials for city and county landfill operations (Cherry Hill landfill and Patapsco landfill), supplying fill for the harbor landfill at Hanover Street, supplying broken rock for the ongoing city erosion control program, and supplying fill for proposed future projects such as the middle Branch Park. For various reasons, none of these projects proved to be suitable. For example, discussions with city and county agencies indicated that no additional materials were required

TABLE 10-5. SUMMARY OF PROJECTS IDENTIFIED FOR MUCK UTILIZATION PROGRAM - PHASE I, SECTION A, BALTIMORE REGION RAPID TRANSIT SYSTEM

	Organization	Potential Muck Utilization Project	Feasibility
I.	City of Baltimore:		
	a. City Planning	Middle Branch Park (Harbor landfill)	Conceptual idea; not funded for further study
	b. City Planning	Erosion Control (Crushed stone slope protection)	Coordination and funding problem
	c. HCD (See letter - Appendix B)	Coldspring - Quarry Backfill	City negotiating with MTA
	d. Public Works Dept. (See letter - Appendix B)	D.P.W. Projects	No fill needed
	e. City Planning	Carlin's Property (Fill for future site development)	Land acquisition incomplete
II.	Baltimore County:		
	a. Public Works Dept. (See letter - Appendix B)	Sanitary Landfill	Muck too pervious for final cover material
III.	State of Maryland:		
	a. Interstate Division Baltimore City	Highway	Already faced with disposal of surplus material
	b. Maryland Port Administration	Harbor Landfill	Land acquisition incomplete
	c. State Aviation Administration	Landfill	Airport expansion plans indefinite
	d. Mass Transit Administration	Temporary backfill stock-pile at proposed Reisterstown Station site	Plans submitted to MTA for review and approval
IV.	Private Sector:		
	a. Sand & Gravel Suppliers	Construction Materials	"Third party" contractural problems
	b. Baltimore Gas & Electric Co.	Spring Garden Station (Harbor landfill)	BG&E negotiating with MTA

for the ongoing city landfill projects. No significant roadway construction projects requiring backfill were located. In fact, the recent highway construction along the Franklin Mulberry Corridor produced a general surplus of earth materials.

Supply of excavated materials to private sector operations such as sand and gravel plants was also investigated. However, "third party" contractual problems developed, represented by MTA interference between a general contractor's construction progress and the rate of supply promised to a private party. Thus, the "sale" of material by the MTA to a private party was not acceptable, although the potential for such an agreement was identified.

10.4.5.4 Recommended Utilization Projects

The proposed muck utilization program was formulated in an attempt to account for disposal of all excavated materials and re-use of some materials for MTA construction purposes. Several of the important criteria which were used in screening appropriate projects included ownership of the land, relative timing of the MTA construction versus proposed backfilling projects, successful application for permits (for harbor filling, for instance), and relative costs for transport of excavated MTA materials to the disposal site. On the basis of these screening criteria, it was determined that the following projects deserved further consideration.

a. Reistertown Station Area. Approximately 5 acres of a 36 acre parcel of land owned by the MTA were available as a stockpile area for future station backfill materials. About 128,000 cu yd of backfill would be stockpiled at the site (Refer to Table 10-6).

b. Coldspring Housing Project. The City of Baltimore Department of Housing and Community Development has planned the Coldspring Housing project and will require earth or rock fill materials to backfill an abandoned quarry. From 150,000 to 500,000 cu yd of fill are needed (Refer to Table 10-7).

c. Baltimore Gas and Electric Co. The Baltimore Gas and Electric Co. is currently constructing a landfill at the Spring Garden Station. The land is being created by filling in about 7 acres of the Baltimore harbor shoreline. About 100,000 cu yd of materials are required (Refer to Table 10-8).

d. Maryland Port Administration. The proposed development of the Brooklyn-Masonville area by the Maryland Port Administration will involve construction of a major landfill. Preliminary estimates indicate that several million cu yd of fill are required (Refer to Table 10-9).

The general location of each proposed utilization site is shown in Figure 10-20. Additional details of the projects and their relationship to the MTA construction project are presented in the following sections.

TABLE 10-6. SUMMARY OF PROPOSED MUCK UTILIZATION PROGRAM - REISTERSTOWN PROJECT

Goal: Stockpile fill material for reuse on MTA projects.

Source of Material: Bolton Hill Station.

Quantity: 140,000± cy of earth.

Reuse of Material:
(Backfill for MTA project)

1. Bolton Hill Station
2. Lexington Market Station
3. Laurens Street Station
4. North Ave Station
5. Mondawmin Station

Economic Advantage: Reduce disposal cost and cost for backfill.

Project Status: Plans and specifications were developed for review by MTA and General Consultant, DMJM/KE.

TABLE 10-7. SUMMARY OF PROPOSED MUCK UTILIZATION PROGRAM - COLDSPRING PROJECT

Goal: Backfill abandoned quarry as part of a planned housing development.

Source of Material: Mondawmin Line and Station.

Quantity and Type of Material: 165,000 to 500,000 cy of earth and rock.

Reuse of Material: No reuse of material; permanent filling of abandoned quarry.

Economic Advantage: Reduce disposal cost for MTA and provide backfill for Baltimore City Project.

Project Status: MTA to negotiate an agreement with the Baltimore City Department of Housing and Community Development to clarify responsibilities.

TABLE 10-8. SUMMARY OF PROPOSED MUCK UTILIZATION PROGRAM - BALTIMORE GAS AND ELECTRIC CO.

Goal: Disposal site and potential stockpile area, by developing landfill, in harbor.

Source of Material: Charles Center Station.

Quantity and Type of Material: 100,000 cy of earth.

Reuse of Material: Backfill Charles Center Station and construction of permanent landfill.

Economic Advantage: Reduce disposal cost and provide backfill for MTA and provide acceptable fill material for BG&E.

Project Status: Maryland Department of Natural Resources has given approval for use of earth as underwater fill behind rubble dike barrier. Further negotiation with BG&E required.

TABLE 10-9. SUMMARY OF PROPOSED MUCK UTILIZATION PROGRAM - MARYLAND PORT AUTHORITY

Goal: Provide fill for use in major landfill and harbor facilities project.

Source of Material: Entire MTA project.

Quantity and Type of Material: 5,000,000± cy of earth and rock.

Reuse of Material: Permanent backfill operation with potential for stockpile area.

Economic Advantage: Provides a convenient disposal and stockpile area for the MTA plus acceptable fill for port development at significant cost savings.

Project Status: Preliminary engineering agreement on use of material but Maryland Port Administration must complete land acquisition process before utilization plans can be finalized.

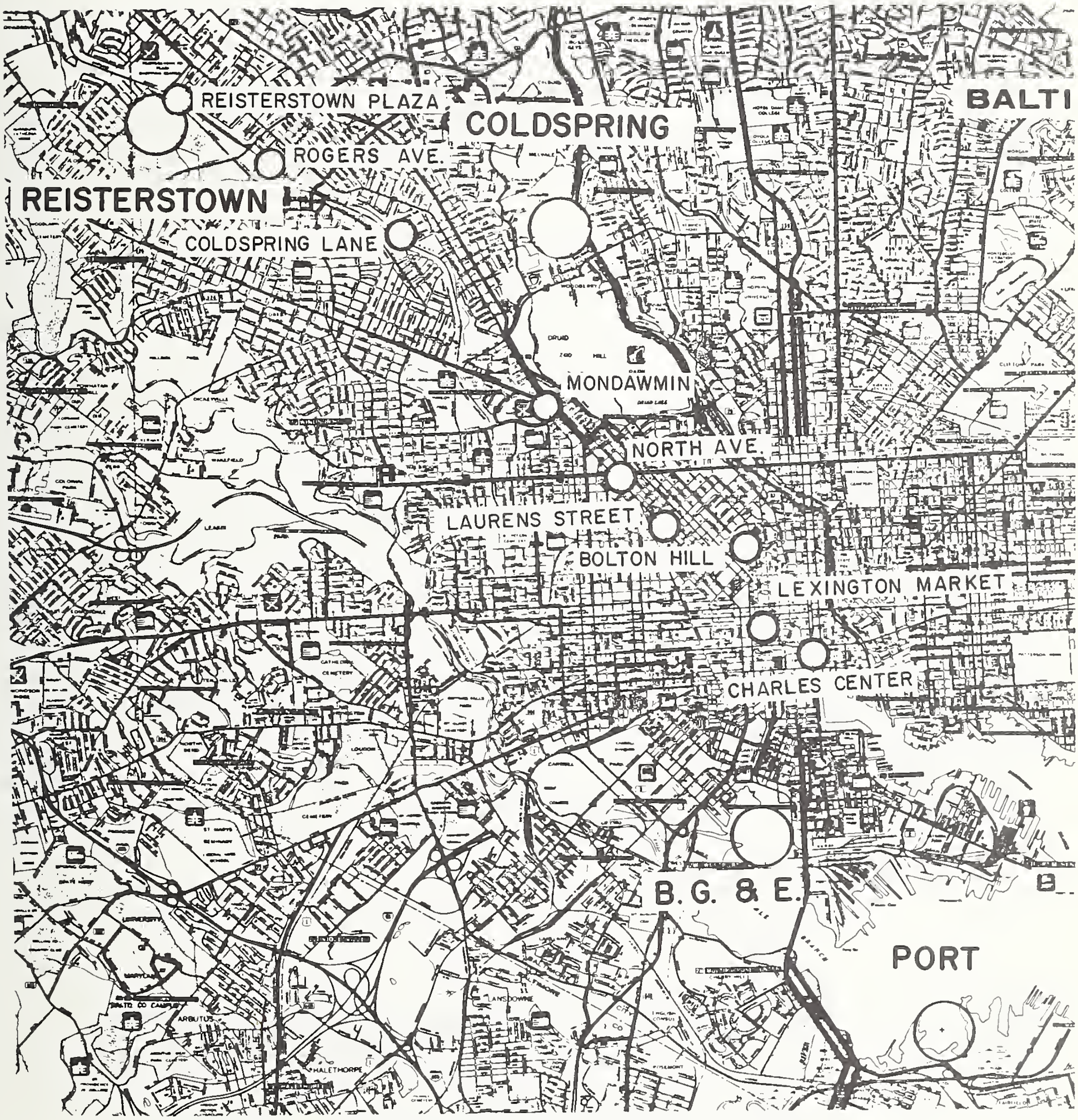
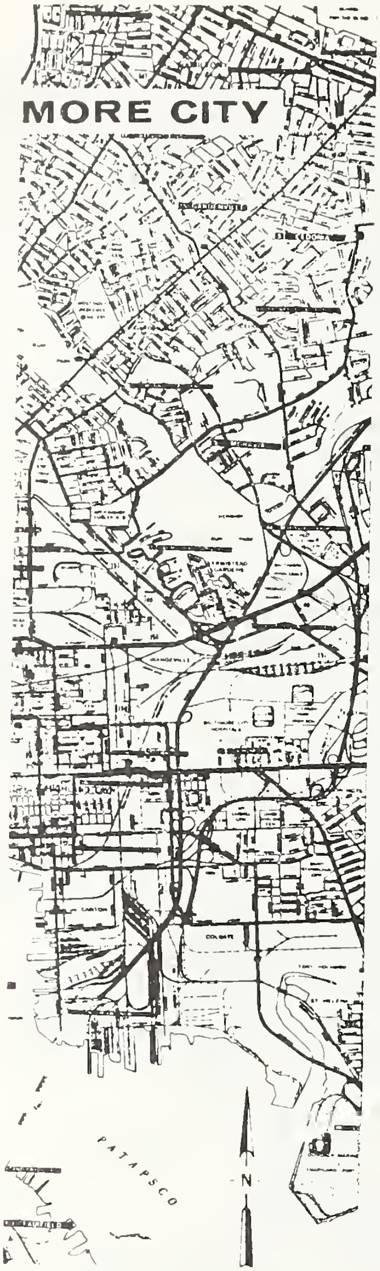


FIGURE 10-20. MUCK DISPOSAL SITES



LEGEND

○ REISTERSTOWN - Stockpile excavated earth materials (130,000 c.y.) from Bolton Hill Station on 5.0± acres of Reisterstown Plaza Station site. Stockpile to serve as source of backfill material for Mondawmin, North Ave., Laurens Street, Bolton Hill and Lexington Market Stations.

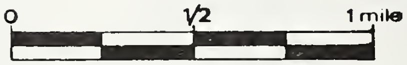
○ COLDSPRING - Backfill abandoned quarry (150,000 + c.y.) in connection with proposed Coldspring Housing Development.

○ B.G.&E. - Provide fill (100,000 ± c.y.) for harbor landfill at Baltimore Gas & Electric Co. Spring Garden Station. Use landfill site to store additional excavated earth materials for subsequent use as backfill for Charles Center Station.

○ PORT - Provide fill (1,800,000 ± c.y.) for Maryland Port Administration proposed development of Brooklyn-Masonville area.

CHARLES CENTER

○ Proposed station location - Phase I Section A Baltimore Region Rapid Transit System



(CONTINUED)

It is intended that each utilization project be presented as an alternative to the traditional procedure of requiring the contractor to dispose of all materials. The contractor would be informed of the alternative disposal plans through information and bid items contained in the contract documents. By preparing alternative items both the contractor and the MTA have the flexibility to choose the more economical disposal plan based on actual marketplace costs.

During the study, it was possible to develop more detailed utilization plans for the Reisterstown stockpile project. This development occurred because the MTA owned the necessary land. Thus, the following description of the Reisterstown project contains considerably more details than the remaining three projects.

10.4.5.4.1 Reisterstown Station Area--Backfill Stockpile

a. Site Location: The Reisterstown parking area will be constructed on the Seton Property located at the intersection of Wabash Avenue and Patterson Avenue, as shown in Figure 10-21. This figure indicates the current plans for site development as prepared by Baker-Wibberly Associates, Inc., architects for this particular construction contract. Note that the proposed stockpile area would cover a future parking area and a portion of the proposed bus turn-around loop. The estimated plan storage area is approximately 5.5 to 6.0 acres and is limited by the existing brook, a sewer line, and by the sloping and tree covered ground on the northerly side of the site. The future development plans or guidelines for the site call for the preservation of as many trees as possible, consistent with parking requirements. Thus, a section of open meadow land was recommended as the stockpile area.

The proposed stockpile area slopes gently toward the brook. The trees and vegetation which have developed adjacent to the brook would be preserved during the stockpiling operation. Based on recent calculations of the high water flows through the culvert beneath Wabash Avenue, the site would not be subject to flooding during the design 10-year storm. Thus, the stockpile does not encroach on a floodplain area.

Access to the site would be gained through a temporary construction haul road leading directly from Wabash Avenue into the stockpile area.

The estimated storage volume for this site is controlled by the boundaries and height of fill. For reasonable fill heights of 25 ft, the 5.5 acre site could hold approximately 140,000 cu yd of material. This capacity exceeds the estimated 128,000 cu yds of material needed to backfill five cut-and-cover stations, as discussed later.

b. Source of Material: Materials excavated from the Bolton Hill Station were recommended as the backfill source because of (1) the timing of the construction contract and (2) the quantity and quality of materials.

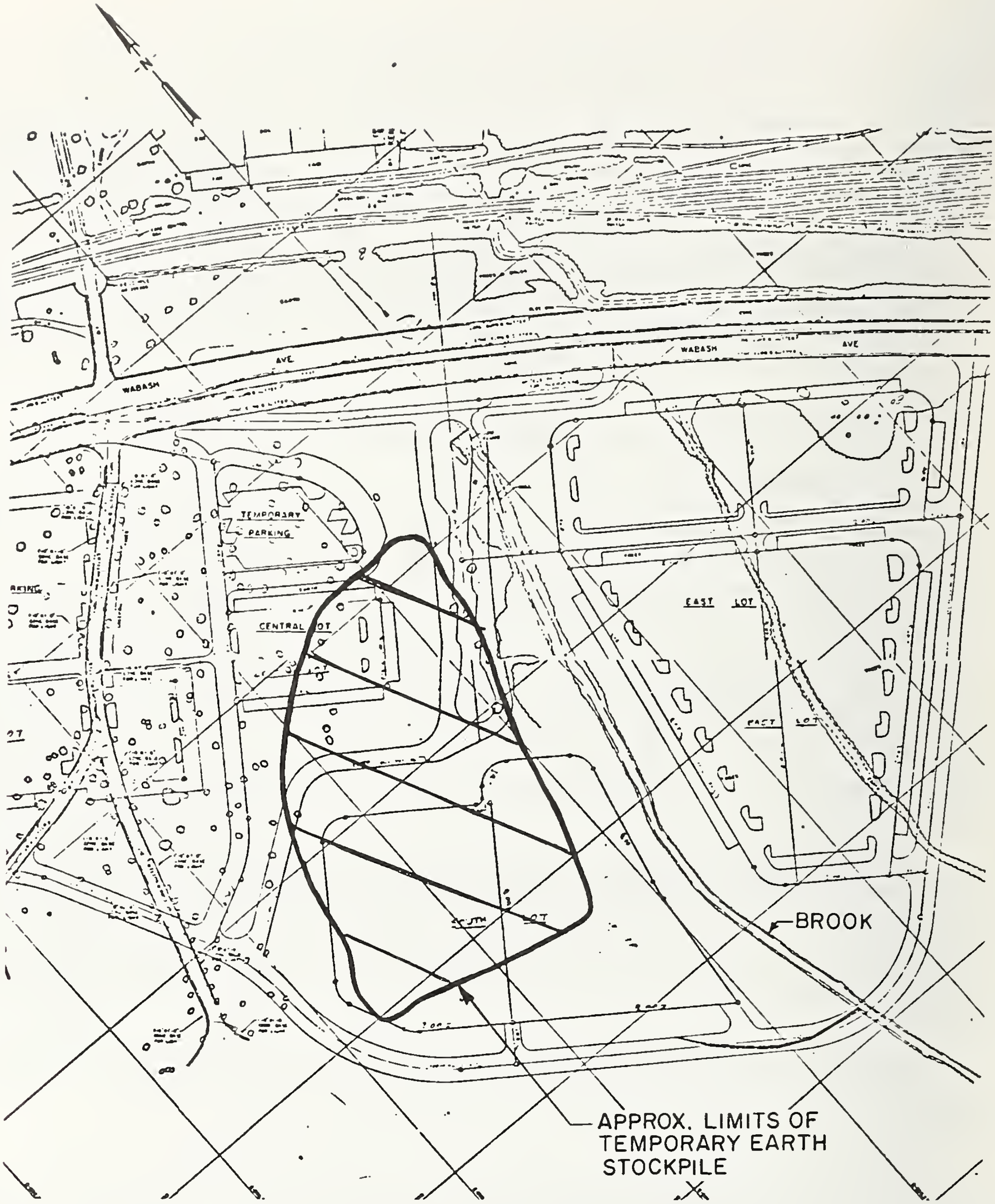


FIGURE 10-21. REISTERSTOWN SITE LOCATION PLAN

The Bolton Hill Station contract would be the second contract to be issued for bidding, and the documents could be prepared including the stockpile option. Thus, the excavation would be completed and the stockpile built early in the overall Phase 1, Section A construction program. Subsequent contracts would then be established to utilize the stockpiled materials for backfill.

The total volume of materials to be excavated at the station was estimated at 140,000 cu yd. Based on an examination of the soil report prepared by Robert B. Balter, Inc. [10-13, 10-14], a layer of fill about 7 ft in thickness was found overlying the site. Since these materials represent potentially unacceptable materials, it was recommended that they be excluded from the stockpile program. Thus the total volume of material available for the stockpile would be reduced to about 130,000 cu yd, almost exactly matching the estimated backfill volumes.

The natural soil deposits encountered in the test boring program were also exposed for inspection and sampling during the construction of a test shaft at the station location [10-14]. The natural soil deposits, generally consist of gravelly coarse to fine sand with trace to little silt content, and thus represent excellent backfill materials.

Gradation curves for typical materials encountered in the excavation of the test shaft were compared against the standard specification requirements "structural fill" and "common fill". The results indicate that the excavated materials will generally satisfy these specification requirements, as shown in Figures 10-22 and 10-23.

c. Proposed Use of Materials: The Reisterstown site would be used to store backfill for five stations. The estimated volumes of backfill are tabulated below:

Station	Backfill Quantities (cu yd)
Mondawmin	22,000
North Avenue	15,000
Laurens Street	25,000
Bolton Hill	51,000
Lexington Market	15,000
Total	128,000

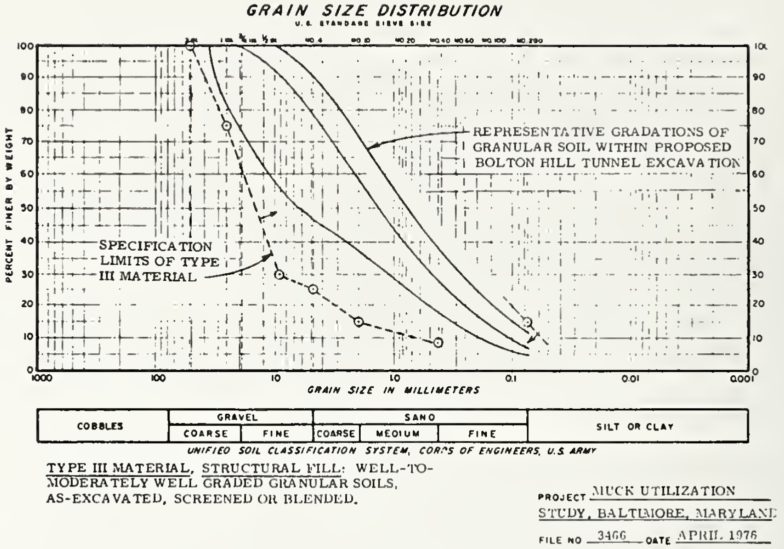


FIGURE 10-22. GRADATION LIMITS OF TYPE III MATERIAL - STRUCTURAL FILL

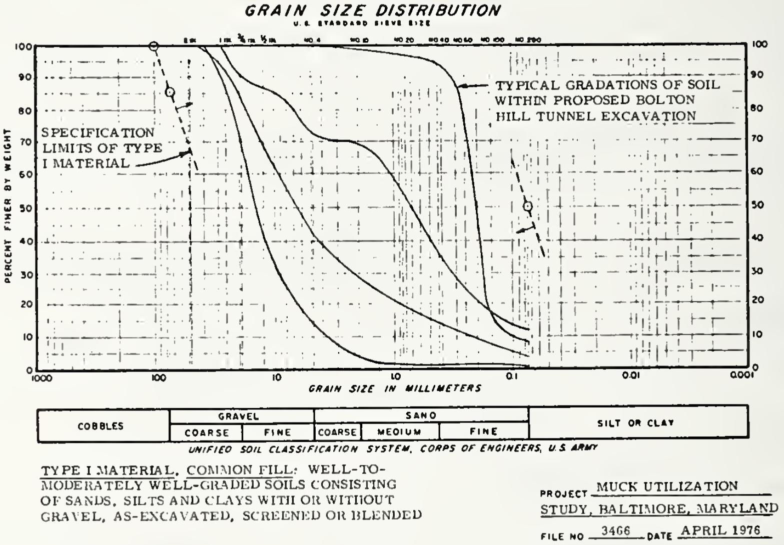


FIGURE 10-23. GRADATION LIMITS OF TYPE I MATERIAL - COMMON FILL

This estimated quantity agrees with the anticipated 130,000 cu yd of acceptable materials from the Bolton Hill Station excavation.

d. Stockpiling Procedures: The primary intent of the procedures to be used in creating the stockpile area was to provide a stable fill area with a minimum of erosion problems. The material would be placed by end-dumping and spreading in layers about 3 ft in thickness, with construction access provided by the contractor as required.

Simple erosion control measures will be implemented, such as providing a gradient of the top of the fill sloping toward the center of the fill area, thus minimizing runoff. Runoff on the slopes will be controlled by spreading a minimum of topsoil on the lower portion of the slope and seeding the slope to provide surface stability. Runoff around the perimeter of the area could be checked by baled hay, while a healthy line of vegetation will be maintained along the existing stream bank. These general measures were reviewed with the Maryland State Department of Natural Resources and appear to be sufficient for the proposed project.

A preliminary site grading plan illustrating the erosion control measures which were developed with the assistance of DMJM/KE is included as Figures 10-24 and 10-25.

e. Economic Comparison: The purpose of providing a stockpile site for the Bolton Hill Station contractor is to (1) provide a disposal area and (2) create a stockpile for backfill materials. The economic benefit to the MTA would be accrued in terms of reducing the contractor's risks and costs associated with normal disposal operations and then having an assured stockpile of material for use as backfill.

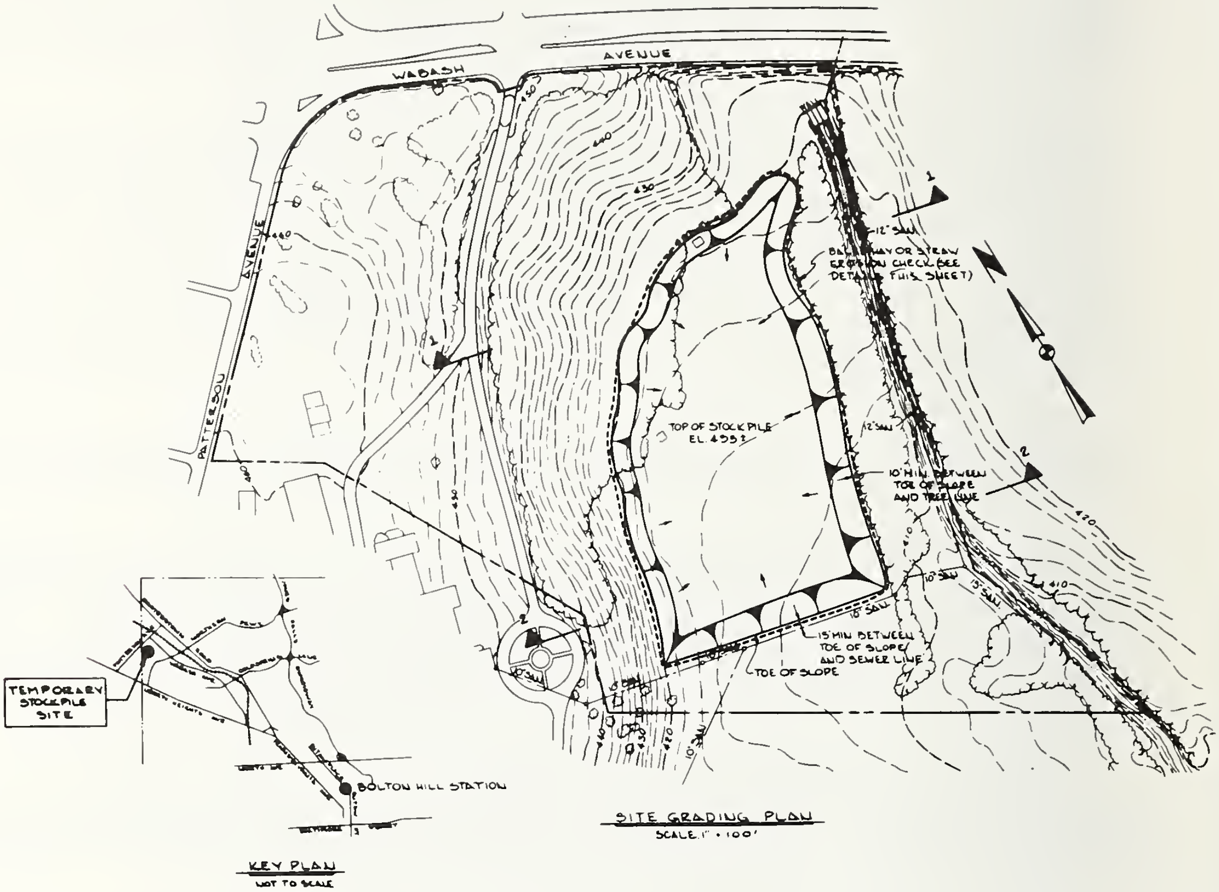
In order to provide a cost comparison, it was recommended that the use of the disposal area be presented to the contractor in the form of an option. The contract documents would be worded in a manner which would present two general alternatives such as:

A: Contractor disposal of material and contractor supply of backfill.

B: Utilization of Reisterstown site for disposal and backfill source.

Under each of the alternatives, a unit pricing schedule would be established for (1) disposal of material and (2) supply of backfill. Thus, upon receipt of bids, the MTA will be able to determine the most economical alternative.

A preliminary economic comparison including items for two-way hauling, placement of material in the stockpile, and maintenance of the stockpile indicated an economic advantage for selection of the stockpile program (Alternative B). The final economic comparison would, of course, be made at the receipt of bids.



[illegible]:

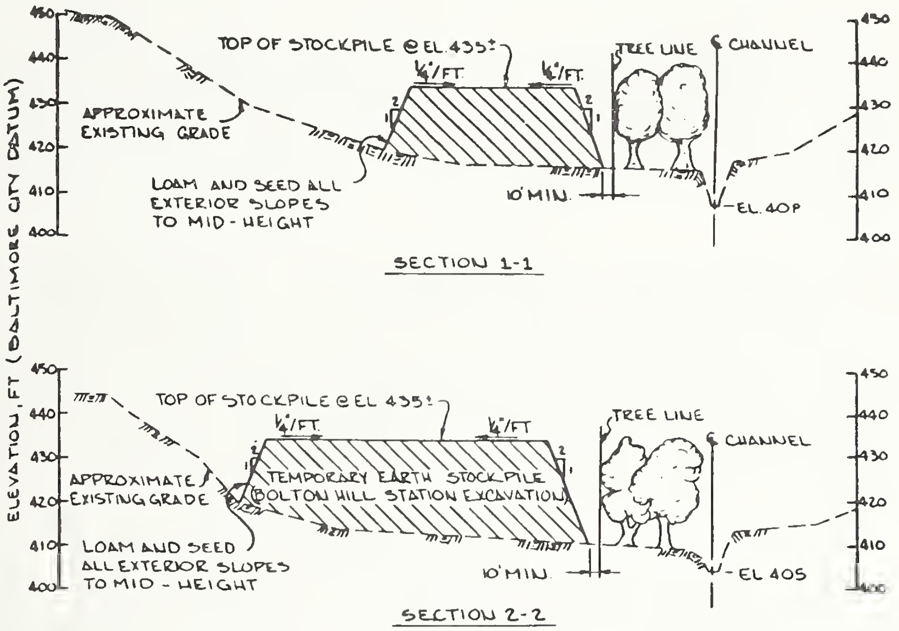
1. Maintain grass or vegetation cover between existing brook and toe of slope of stockpile.

2. Location of existing sewer line to be confirmed by field survey prior to construction of stockpile.

3. Site preparation includes removal of trees and structures within proposed stockpile area.

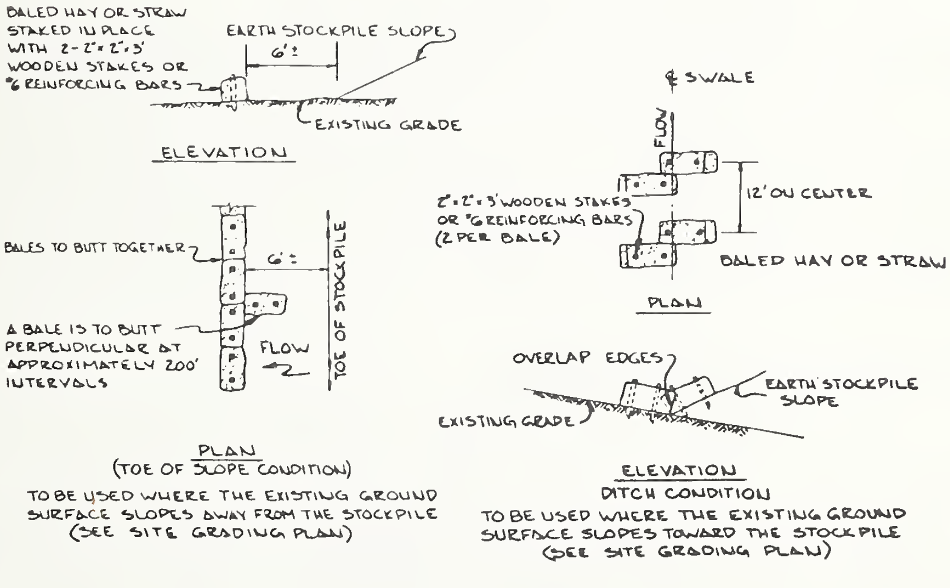
4. Site access to be developed from Wabash Ave.

FIGURE 10-24. PRELIMINARY SITE GRADING PLAN


ELEVATION, FT (BALTIMORE CITY DATUM)
450
440
430
420
410
400
TOP OF STOCKPILE @ EL. 435±
¼"/FT.
¼"/FT.
2
1
2
1
TREE LINE
℄ CHANNEL
APPROXIMATE EXISTING GRADE
LOAM AND SEED ALL EXTERIOR SLOPES TO MID-HEIGHT
10' MIN.
EL. 40P
SECTION 1-1
TOP OF STOCKPILE @ EL 435±
¼"/FT
¼"/FT
TREE LINE
℄ CHANNEL
APPROXIMATE EXISTING GRADE
TEMPORARY EARTH STOCKPILE (BOLTON HILL STATION EXCAVATION)
LOAM AND SEED ALL EXTERIOR SLOPES TO MID-HEIGHT
10' MIN.
EL 405
SECTION 2-2

TYPICAL SECTIONS

SCALE: 1"=100' HORIZ, 1"=20' VERT.


BALED HAY OR STRAW STAKED IN PLACE WITH 2-2"×2"×3' WOODEN STAKES OR #6 REINFORCING BARS
EARTH STOCKPILE SLOPE
6'±
EXISTING GRADE
ELEVATION
BALES TO BUTT TOGETHER
6'±
TOE OF STOCKPILE
A BALE IS TO BUTT PERPENDICULAR AT APPROXIMATELY 200' INTERVALS
FLOW
PLAN
(TOE OF SLOPE CONDITION)
TO BE USED WHERE THE EXISTING GROUND SURFACE SLOPES AWAY FROM THE STOCKPILE (SEE SITE GRADING PLAN)
℄ SWALE
FLOW
12' ON CENTER
2"×2"×3' WOODEN STAKES OR #6 REINFORCING BARS (2 PER BALE)
BALED HAY OR STRAW
PLAN
OVERLAP EDGES
EARTH STOCKPILE SLOPE
EXISTING GRADE
ELEVATION
DITCH CONDITION
TO BE USED WHERE THE EXISTING GROUND SURFACE SLOPES TOWARD THE STOCKPILE (SEE SITE GRADING PLAN)

DETAILS OF BALED HAY OR STRAW EROSION CHECK

NOT TO SCALE

FIGURE 10-25. PRELIMINARY SITE GRADING PLAN (SECTIONS)

f. Contract Considerations: In order to include the stockpile alternative in the Bolton Hill Station contract, the standard specifications are being revised. A preliminary set of documents outlining basic changes applicable to the Bolton Hill Tunnel contract was prepared in conjunction with DMJM/KE. The proposed specifications were included in a "Status Report" prepared by Haley & Aldrich [10-15]. Basic changes apply to the presentation of alternative bid items for muck disposal and supply of backfill, as well as maintenance of the stockpile area.

Other changes are also required in sections of the contract dealing with the quality of backfill materials. For instance, as already noted, the contractor will be requested to provide a unit price using the Bolton Hill stockpile area as an alternative source for backfill. Since this backfill would be MTA property, the contractor could not be held responsible for the gradation of the material. However, as noted previously, the available gradation test data indicate that the excavated materials will satisfy the standard specification requirements for structural and common backfill. The materials will be cohesionless and can be compacted by standard construction equipment, so that no modification of compaction standards will be required.

The Reisterstown construction contract will also require some modification in order to alert the contractor to the existence of the backfill stockpile at the parking lot and bus loop area. However, since there is ample construction room at the Reisterstown Plaza area, it is anticipated that staged construction could be used and the stockpile would not be an obstacle at that construction site.

g. Conclusions and Recommendations: Based on the required needs for backfill on the MTA project and the anticipated economic advantage for the use of a stockpile site, it was recommended that the Bolton Hill Station contract be modified to include a provision for the Reisterstown stockpile program. The contract package will be structured to provide for alternative choices between disposal of excavated materials and supply of backfill totally by the contractor's methods versus disposal of materials and supply of backfill at the proposed Reisterstown stockpile. Thus, the relative prices of the alternative methods can be readily evaluated and the most economical choice can be made by the MTA.

10.4.5.4.2 Coldspring Project

a. Summary: The City of Baltimore is currently planning and, in fact, has already begun phased construction of a new in-town community, referred to as the Coldspring Project, in northwest Baltimore as shown in Figure 10-20. As part of this new development, it is planned to construct high rise apartments around the periphery of an abandoned water-filled quarry. The quarry itself would serve as a recreational lake. In order to achieve a planned lake depth of 10 ft, it will be necessary to fill the quarry. It is proposed that excavated rock from the Mondawmin Station and/or tunnel excavations be used for the quarry fill. A complete description of the Coldspring project can be found in a report prepared by Moshe Safdi, architect for the project [10-16].

b. Proposed Utilization Plan: It was recommended that excavated materials from the MTA project be supplied to the City of Baltimore for use in backfilling the Coldspring quarry in the development of a recreational lake. The basic premise of this utilization program is to minimize both the cost of disposal of materials to the MTA and the cost of obtaining fill materials by the City of Baltimore.

Haley & Aldrich, Inc. reviewed details of the Coldspring project with the City of Baltimore Department of Housing and Community Development (HCD). Plans relative to housing design and related improvements in the quarry area have not been finalized to date. Thus, final elevations including design lake bed elevation have not been set, and the exact volume of fill required to fill the quarry is uncertain at this time. However, the City has indicated that at least some of the required filling could take place prior to these determinations.

Based on topographical plans supplied to Haley & Aldrich, Inc. by Mr. Merrill, an estimate was made of the volume of fill materials required to backfill the quarry to selected elevations. The results are presented in Figure 10-26. HCD has indicated that the lake bed level could range between El. 120 and El. 160; corresponding fill volumes could range from 165,000 to 525,000 cu yd. At this time, HCD is willing to fill the quarry to El. 120 and, therefore, about 165,000 cu yd of fill will be required (possibly as a first phase filling operation).

Both excavated earth and rock materials from the MTA project will comply with the Coldspring project specifications for quarry fill [10-17]. Rock is favored for the quarry fill, at present, due to:

a. The proximity of the quarry to the construction sites for the Mondawmin Station and/or Tunnel portal

b. The possibility of placing an underwater fill in the quarry, thus minimizing dewatering costs

The City of Baltimore has agreed in principle to the recommended utilization plan. The MTA and City will have to refine details relative to coordinating disposal at the Coldspring project and discuss formulation of an agreement between the MTA and City relative to the utilization program outlined.

10.4.5.4.3 Baltimore Gas and Electric Co. - Landfill

a. Site Location: The Baltimore Gas and Electric Company (BG&E) has obtained the required permits for construction of a landfill at the Spring Garden Station located on the Middle Branch of Baltimore Harbor, as shown in Figure 10-20. About seven acres of the harbor will be filled to create additional storage area for utility equipment and materials.

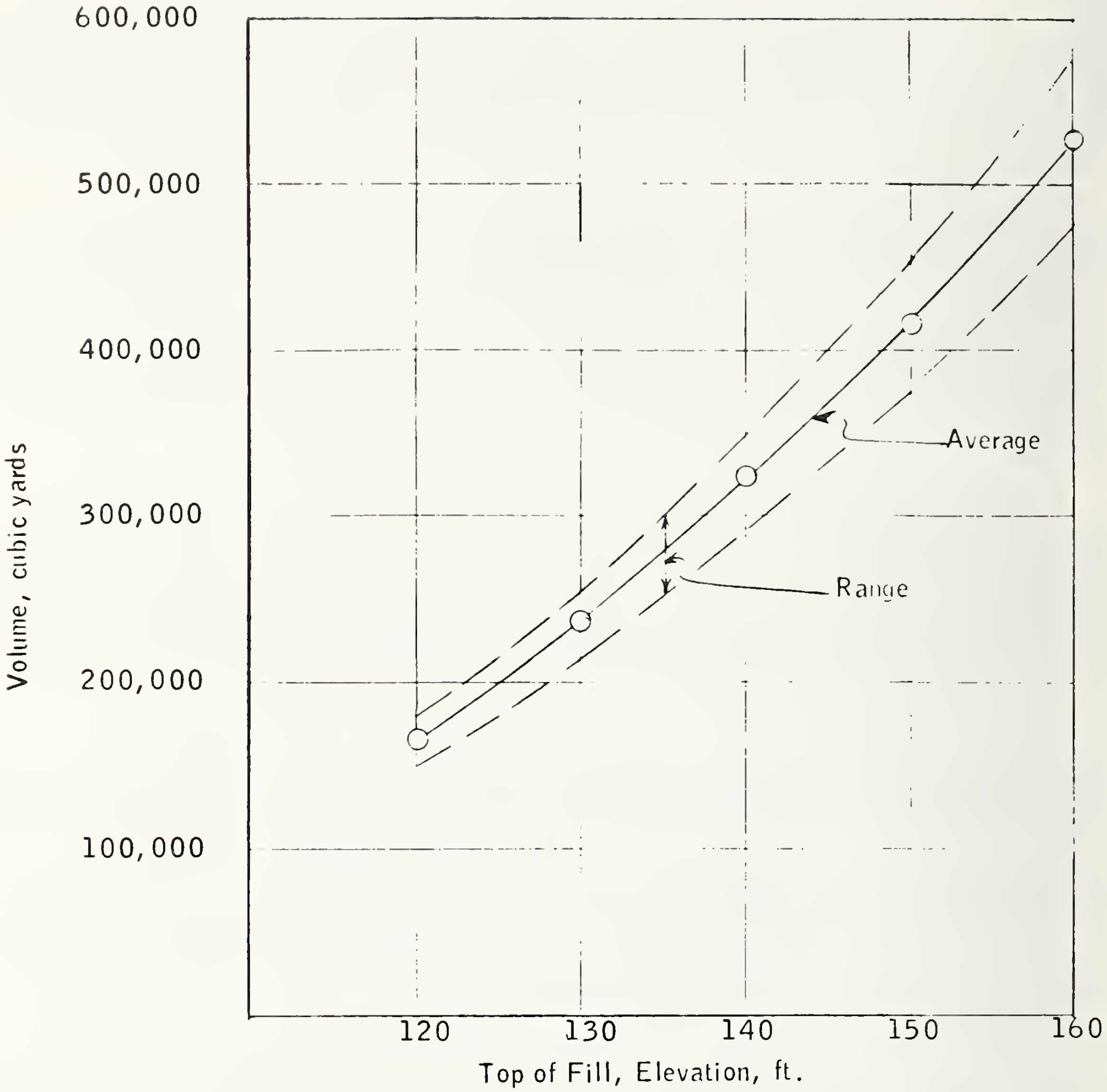


FIGURE 10-26. QUARRY BACKFILL QUANTITY ESTIMATE - COLDSPRING COMMUNITY

According to the requirements of the fill permits, materials used in the landfill must consist of clean rubble fill such as broken concrete or bricks from building demolition projects. Construction of a rubble fill access dike perpendicular to the shoreline has been initiated.

b. Source of Materials: It was proposed that materials excavated from the Charles Center Station be used in the BG&E landfill program. The materials would consist of inorganic soils such as gravelly sands, sandy gravels, or silty sands which have been identified by the test borings at the Charles Center Station site [10-18].

c. Potential Use: The excavated materials would be used as general fill in the BG&E landfill. After completion of the landfill, it was proposed that sufficient material be stockpiled on the landfill for re-use as backfill at the Charles Center Station. The temporary stockpile would also serve as a surcharge load and help to stabilize the long-term settlement of the BG&E landfill.

Preliminary approval has been obtained from the Maryland Department of Natural Resources for use of earth materials from the MTA construction as fill in this underwater fill project, provided that the material is contained within a dike. The diking procedure is compatible with BG&E plans for site development.

d. Quantity of Materials: The estimated volume of excavation at Charles Center Station is 254,000 cu yd. About 30,000 cu yd of backfill are required.

The BG&E landfill will probably require a minimum of 100,000 cu yd; the final volumes will depend on the effects of displacement and settlement during filling. The station contractor would be required to dispose of the surplus material either at another utilization site, such as the Port, or by his own methods.

e. Conclusions and Recommendations: The proposed filling and stockpiling program would provide the MTA with a disposal and stockpile area close to the Charles Center Station and would provide BG&E with a preferred fill material rather than miscellaneous rubble fill delivered over a shorter time frame.

Additional negotiations between the MTA and BG&E are underway to establish a working agreement.

10.4.5.4.4 Maryland Port Administration

a. Summary: The Maryland Port Administration has been planning a long-term harbor development program involving a major landfill operation at the Brooklyn Masonville site shown in Figure 10-20. However, since the Port has not yet purchased the property, site development plans have not been advanced beyond the preliminary stage. The tentative timetable for land acquisition indicates that land purchase may be completed during the spring of 1977.

More than 200 acres of land would be developed through a combination of grading of existing contours and placement of underwater fill out to the bulkhead line. Preliminary engineering studies completed by the Port indicate the need for five million cu yd of fill materials.

b. Proposed Muck Utilization Program: The potential for use of tunnel muck in the harbor development plan has been reviewed with representatives of the Port and MTA. Agreement was reached, in principle, that a muck utilization program would be very compatible with the harbor development plans and the transit construction program. Both earth and rock materials would be acceptable as fill materials. Also, sufficient area is available for creation of a stockpile for future backfilling needs.

Continued discussion and negotiation between the MTA and the Port are required in order to establish a working agreement, pending successful land purchase arrangements by the Port.

10.4.6 Conclusions

The study of alternative methods of disposal or utilization of materials excavated from the construction of Phase 1, Section A, rapid transit tunnels and stations was completed by Haley & Aldrich, Inc., as part of a research and development program sponsored by the United States Department of Transportation, Urban Mass Transit Administration through the Transportation Systems Center.

It was concluded that:

a. Utilization of excavated materials is feasible and offers benefits to both the MTA and other city and state organizations currently planning landfill projects.

b. The anticipated materials will consist of soil and broken rock which will be suitable for use as backfill on construction projects. Soil materials will range from gravelly sand to silty sand, while rock will range from soft, moderately weathered schist to very hard, fresh gabbros and amphibolites.

c. Coordination of the rate of production of excavated materials with the rate of use is a controlling aspect of any utilization program. Therefore, the proposed utilization projects were selected for compatibility with "stop and go" rates of delivery of fill materials.

The MTA is providing follow-up support on the four utilization projects, as described in Section 10.4.5.4 of this report. This effort includes completion of formal agreements with other agencies, where required, and adjustments to the standard MTA construction documents to establish alternative muck disposal programs.

11. SUMMARY OF CONCLUSIONS

The principal conclusions of this study are summarized below:

11.1 TRADITIONAL PRACTICE OF MUCK UTILIZATION

Traditionally, very little if any planning for utilization of tunnel muck has been undertaken by transit agencies in the United States. In most cases which were investigated, the tunneling contractor, or trucking subcontractor, becomes the "owner" of the excavated muck materials, often resulting in sporadic planning efforts for disposal. This "unplanned" approach by contractors frequently results in arbitrary landfill uses for the muck. In many instances, a potentially valuable material is wasted, without any consideration for its use.

Detailed analysis of three current muck utilization case studies indicates that a lack of planning and rigid material specifications are the main reasons for arbitrary utilization of muck as landfill.

11.2 TECHNICAL ASSESSMENT OF MUCK PROPERTIES

The technical assessment of muck properties requires completion of a thorough subsurface exploration and laboratory testing program and an evaluation of the probable excavation methods. The wide range of construction equipment and methods available today can produce a wide variety of muck gradations. Current field exploration and laboratory soil and rock testing methods are adequate for evaluating engineering properties of muck. In some cases, additional explorations or modifications of standard sampling techniques may be necessary for retrieving large sample quantities for laboratory testing. The estimated costs for additional field exploration and laboratory testing, compared with standard design costs, are summarized in Table 4-12. A minimum additional cost for evaluating muck potential for landfill will usually range from 1 to 3 percent of standard subsurface exploration costs. These costs will increase substantially, to 30 or even 50 percent of standard subsurface exploration costs, when evaluating specialized utilization programs.

The potential uses for muck can be divided into two general categories: (1) construction material, and (2) specialized uses. Use as a construction material involves a wide variety of placement techniques ranging from engineered, compacted fill to uncontrolled fill. A few examples of specialized uses include the manufacture of fired clay products, lightweight aggregates, portland cement and pavement base course materials. Table 5-1 gives a detailed listing of the various potential uses and ranks the suitability of different muck types for each use. If warranted, the engineering properties of muck can be improved for a particular use by implementing many of the standard techniques used in the foundation construction industry.

11.3 MUCK UTILIZATION PLANNING CONCEPTS

Prior to the direct planning for muck utilization, the contingency problems related to subsurface conditions, method of construction, delays in construction program, and satisfying utilization specifications must be considered. Thorough planning and flexibility can minimize the potential problems.

As described in Section 7, completion of six planning steps are required for developing technically suitable muck utilization plans. These steps are summarized below:

a. Establish route alignment and complete preliminary test borings.

b. Conduct preliminary muck evaluation.

c. Complete subsurface and laboratory testing.

d. Evaluate probable method of construction and muck characteristics.

e. Evaluate potential uses for the muck.

f. Prepare recommendations.

The development and implementation of a muck utilization program is symbolized by three key elements: education, planning, and commitment. First, the transit authority must realize the potential value of the excavated materials (education). Second, a program must be undertaken for the purpose of developing the potential muck utilization schemes (planning). Third, and most important, the muck utilization scheme(s) must be reflected in the contract documents for purposes of bidding and construction (commitment). It is recommended that a Muck Utilization Coordinating Committee (MUCC) be established to implement the muck utilization program.

11.4 HANDBOOK EVALUATION

A handbook, which provides a concise description of the muck utilization concepts, was developed during the course of the overall study. Prior to final preparation, the handbook was reviewed by various transit authority personnel. Section 9 of this report summarizes the comments and suggestions which were received.

11.5 EVALUATION OF PLANNING CONCEPTS BY CASE STUDY

An investigation of the muck disposal planning efforts for three U.S. cities illustrates that a meaningful and practical approach to the problem of muck utilization can be implemented. These cities, Chicago, Atlanta, and Baltimore, are currently expanding existing facilities or constructing new rapid transit systems. The planning concepts described in this report were implemented and a muck utilization plan was developed for a portion of the proposed rapid transit construction in Baltimore.

12. REFERENCES

Abbreviations of Publications

ASCE	American Society of Civil Engineers
ASCE JSMFD	ASCE Journal of Soil Mechanics and Foundation Division
ASCE JCD	ASCE Journal of Construction Division
ASCE JPD	ASCE Journal of Power Division
ASCE TEJ	ASCE Transportation Engineering Journal
CE	Civil Engineering
ENR	Engineering News-Record
1st RETC	Proceedings 1st North American Rapid Excavation and Tunneling Conference, Chicago, Illinois, 5-7 June 1972 (2 Volumes)
2nd RETC	Proceedings 1974 Rapid Excavation and Tunneling Conference San Francisco, California, 24-27 June 1974 (2 Volumes)
JBSCES	Journal of the Boston Society of Civil Engineers Section
ASTM STP	ASTM Standard Technical Paper
TT	Tunnels & Tunnelling
RS	Roads and Streets
CEPWR	Civil Engineering and Public Works Review

Section 2

2-1. "The Hoosac Tunnel," A Brief Report of the Hearing of the Troy and Greenfield Railroad Company Petitioners for A Loan of Two Millions Before A Joint Special Committee of the Legislature of Massachusetts, 9 February 1853, (copy obtained in Archives, State House Library, Boston, Massachusetts)

2-2. Beaver, P., *A History of Lighthouses*, The Citadel Press, 1973

2-3. Sandstrom, G., *Tunnels*, Holt, Reinhart and Winston, 1963

2-4. MacDonald, F., "The Thames Tunnel," Underground Services, Vol. 2, No. 2, 1974

2-5. Personal Communication with Mr. Richard Tilder Smith, Editor of Underground Services, Foundation Publications, Ltd., Doddinchuret, Essex, England

2-6. __________, "Crosstown Wastewater Interceptor, Austin, Texas," fact sheet from ASCE Speciality Conference on Analysis and Design in Geotechnical Engineering, June 1974

2-7. Kimmons, G. H., "Pump Storage Plant At Raccoon Mountain in USA," TT, Vol. 4, No. 2, March 1972, pp. 108-113

Section 2 (cont'd)

2-8. Murphy, W. D., "Machine Tunneling Under Houston," CE, Vol. 34, No. 9, September 1964, pp. 44-45

2-9. Bensch, E., "Excavations and Lining the Sonnenberg Tunnel," TT, Vol. 5, No. 5, September 1973, pp. 443-450

2-10. __________, "Rail Tunnel in Rock, Speeds B.C. Trains," TT, Vol. 4, No. 6, November, 1972, p.547

2-11. __________, "St. Gotthard," TT, Vol. 4, No. 5, November 1972, pp. 407-411

2-12. Kapp, M., "Slurry Trench Construction for Basement Wall of World Trade Center," CE, Vol. 39, No. 4, April 1969, pp. 36-40

2-13. __________, "Crushing Plant Mobility Is Key to Contractor's Profit," RS, May 1971

2-14. __________, "Crushing Converts Rubble into Subbase Aggregate," RS, May 1971, pp. 44-45

2-15. __________, "Offshore Airport Sites on Rock Fill," ENR, 10 April 1975

2-16. Alldredge, W. S., "Washington Metropolitan Area Transit Authority's Experience With Contractual Relationships in Tunneling Contracts," 2nd RETC, Vol. 2, pp. 1137-1162

2-17. Excerpt from Standard MBTA Construction Specification, Section 120.60

2-18. Standing Subcommittee No. 4, Contracting Practices of the U.S. National Committee on Tunneling Technology, Better Contracting for Underground Construction, NTIS PB-236 973, 1974

2-19. Mueser, Rutledge, Wentworth & Johnston, "Subsurface Investigation - Volume 4, Washington Metropolitan Area Rapid Transit Authorized, Basic System Benning Route, and A Portion of the Pentagon Route, NTIS PB-185 757, July 1969

2-20. Contract Documents D4a, Washington Metropolitan Area Transit Authority, May 1972

2-21. Mueser, Rutledge, Wentworth & Johnston, "Washington Metropolitan Area Rapid Transit Authorized Basic System Connecticut Avenue Route, Subsurface Investigation," Vol. 1, NTIS PB-179 653, December 1967

2-22. Contract Documents A6a, Washington Metropolitan Area - Transit Authority, September 1972

2-23. Personal Communication with Langan Engineering Associates, Inc., Consulting Civil Engineers, Clifton, NJ

Section 3

3-1. Bruce, W. E. and Morrell, R. J., "Rapid Excavation in Hard Rock: A State-of-the-Art Report," Proceedings from Deep Tunnels in Hard Rock, The University of Wisconsin-Milwaukee, 9-10 November 1970

3-2. Weber, E., "European Development and Experience with Mechanical Moles in Hard Rock Tunneling," Proceedings from Deep Tunnels in Hard Rock, The University of Wisconsin-Milwaukee, 9-10 November 1970

3-3. Jacobs, J. D., "An Innovation in Machine Tunneling," 2nd RETC, Vol. 2, pp. 1683-1696

3-4. McCusker, T. G. and Dietl, B., "Small Diameter Tunnels in Manhattan Schist," 2nd RETC, Vol. 1, pp. 265-281

3-5. Wang, Fun-Den, Miller, R. and Ozdemir, L., "Improving Hard Rock Tunneling Through Comparison of Laboratory and Field Tunnel Boring Studies," 2nd RETC, Vol. 2, pp. 1741-1757

3-6. Takaoka, S., Hayamizu, H., and Misawa, S., "Studies on the Cutting of Rock by Rotary Cutters (Part 1 and 2)," TT, Vol. 5, No. 2 and 3, March and May 1973, pp. 181-185

3-7. Mellor, M. and Hawkes, I., "Hard Rock Tunneling Machine Characteristics," 1st RETC, Vol. 2, pp. 1149-1158

3-8. Gaye, F., "Efficient Excavation-Cutter Head Design of Hard Rock Tunneling Machines (Part 1 and 2)," TT, Vol. 4, No. 1 and 2, January and March 1972, pp. 39-48, pp. 135-143

3-9. Hignett, H. J. and Tough, S. G., "Tunneling Trials by Transport and Road Research Laboratory," 2nd RETC, Vol. 2, p. 1697

3-10. Cook, G. W., "Analysis of Hard-Rock Cuttability for Machines," Proceedings of the Tunnel and Shaft Conference, Minneapolis, Minnesota, 15-17 May 1968

3-11. Barendsen, P., "European Development and Experience with Mechanical Moles in Hard Rock Tunneling," Proceedings from Deep Tunnels in Hard Rock, the University of Wisconsin-Milwaukee, 9-10 November 1970

3-12. "Fullfacer Tunneling Machines," brochure prepared by Atlas Capco, Inc., New Jersey, March 1973

3-13. Rad, P. F., "Muck Evaluates Machines," TT, Vol. 7, No. 1, January 1975, pp. 30-33

3-14. Haller, H. F. and Pattison, H. C., "Predicting Materials Handling Properties of Tunnels," 1st RETC, Vol. 2, pp.1279-1296

3-15. Haller, H. F., "Study of Interrelationship of In-Situ Rock Properties, Excavation Method, and Muck Properties," Final Report to Advanced Research Project Agency, NTIS No. AD-742 781, July 1973, 284 pp.

3-16. Saperstein, L. A. and Raab, D. E., "The Effect of Rock Type and Tunneling Machine on Bulk Material Handling Parameters," 2nd RETC, Vol. 1, pp. 711-727

3-17. Earth Manual, United States Department of the Interior, Bureau of Reclamation, 1963

3-18. Raab, D. E., "Variations in the Angle of Internal Friction with Particle Size and Size Consist for Mechanically-Chipped Material," M. S. Thesis, Pennsylvania State University, August, 1973, 163 pp.

3-19. Blaster's Handbook, 15th ed., E. I. duPont de Nemours & Co., Inc., 1969

3-20. Nicholls, H. R. and Duvall, W. I., "Effects of Charge Diameter on Explosive Performance," Bureau of Mines Report Investigation 4806, U. S. Department of the Interior, 1966

3-21. Langefors, U. and Kihlstron, B., Rock Blasting, 2nd ed., John Wiley & Sons, Inc., 1963, 405 pp.

3-22. Guistafson, R., Swedish Blasting Technique, SPl, Gothenburg, Sweden, 1973, 323 pp.

3-23. Just, G. D., "The Application of Size Distribution Equations to Rock Breakage by Explosives," Journal of the International Society of Rock Mechanics, Vol. 5, No. 3, September 1973

3-24. Duvall, U. I. and Atchison, T. C., "Rock Breakage by Explosives," Bureau of Mines Report of Investigations 5356, U. S. Department of the Interior, 1957

3-25. Duncan, J. M. and others, "Materials Handling for Tunneling," Final Report for the Office of High Speed Ground Transportation and the Urban Mass Transportation Administration, Report No. FRA-RT-71-57, 1970, 614 pp.

3-26. Mayo, R. S., "Rapid Muck Haulage," 2nd RETC, Vol. 1, pp. 419-426

3-27. Faddick, R. R. and Martin, J. W., "Pneumatic-Hydraulic Material Transport System for Rapid Excavation of Tunnels," Final Report for U. S. Department of Transportation, DOT-TST-75-17, 1974, 128 pp.

Section 3 (cont'd)

3-28. Chrysanthou, C. G., "Experience in Edmonton, Canada with Emphasis on Pneumatic Conveyance of Muck," Proceedings from Deep Tunnels in Hard Rock, The University of Wisconsin-Milwaukee, 9-10 November 1970

3-29. Morrison, B. H., "Pneumatic Transport Systems," 1st RETC, Vol. 2, pp. 1251-1265

3-30. Proctor, R. J. and Hoffman, G. A., "Planning Subways by Tunnel or Cut-And-Cover: Some Cost-Benefit Comparisons," 2nd RETC, Vol. 1, pp. 51-63

3-31. Taylor, D. W., Fundamentals of Soil Mechanics, John Wiley & Sons, Inc., 1948, pp. 454-462

3-32. Tschebotarioff, G. P., Foundations, Retaining and Earth Structures, 2nd ed., McGraw Hill Book Company, 1973, pp.415-457

3-33. USS Steel Sheet Piling Design Manual, prepared by United States Steel, Pittsburgh, Pennsylvania, September 1970, 132 pp.

3-34. Haffen, M. and Janin, J., "Grouting Cohesionless Water Bearing Soils in City Tunnels," 1st RETC, Vol. 2, pp. 1539-1568

3-35. Anderson, E. R. and McCusker, T. G., "Chemical Consolidation in a Mixed Face Tunnel," 1st RETC, Vol. 1, pp. 315-329

3-36. Flataw, A. S., Brockett, R. W. and Brown, J. V., "Grouts and Grouting - A Survey of Materials and Practice," CEPWR, July 1973

3-37. Shuster, J. A., "Controlled Freezing for Temporary Ground Support," 1st RETC, Vol. 2, pp. 863-895

3-38. Gail, C. P., "Tunnel Driven Using Subsurface Freezing," CE, Vol. 42, No. 5, May 1972, pp. 37-39

3-39. Hartmann, R. E. and Piggott, D. E., "Construction of Port Huron, Michigan, Intake Shaft," 2nd RETC, Vol. 2, pp. 1201-1211

3-40. Sanger, F. J., "Ground Freezing in Construction," ASCE JSMFD, Vol. 94, No. SM1, January 1968, pp. 131-158

3-41. Fillip, N. M., "Material Handling Consideration in Bored Tunnels," 2nd RETC, Vol. 1, pp. 457-479

3-42. Boden, J. B. and McCaul, C., "Measurement of Ground Movements During A Bentonite Tunneling Experiment," Transport and Road Research Laboratory, Department of Environment, Report 653, Crowthorne, Berkshire, 1974

Section 3 (cont'd)

3-43. A film "The Bentonite Tunneling Machine," presented by Mott, Hay, and Anderson, Consulting Civil Engineers at the 2nd RETC

3-44. Olson, J. J., "Rapid Excavation Research - Elements of a New Excavator Technology," 2nd RETC, Vol. 2, pp. 1503-1535

3-45. Carstens, J. P., "Thermal Fracture of Rock - A Review of Experimental Results," 1st RETC, Vol. 2, pp. 1363-1392

3-46. Lundquist, R. G., "Underground Tests of the REAM Method of Rock Fragmentation for High Speed Tunneling," 2nd RETC, Vol. 1, pp. 825-840

3-47. Cooley, W. C., "Water Jets and Rock Hammers for Tunneling in the US and USSR," 1st RETC, Vol. 2, pp. 1325-1360

3-48. Cooley, W. C., "Rock Disintegration Tests of a Water Cannon," 2nd RETC, Vol. 1, pp. 805-823

3-49. Rowley, J. C. and others, "Rock Melting Subterrenes - Their Role in Future Excavation Technology," 2nd RETC, Vol. 2, pp. 1777-1796

3-50. Williams, R. E., "Soil Melting - A Practical Trial," TT, Vol. 7, No. 1, January 1975, pp. 44-45

Section 4

4-1. Lambe, T. W., Soil Testing for Engineers, John Wiley & Sons, Inc., 1951, pp. 8-11, 110-121, 74-87, 31

4-2. Terzaghi, K. and Peck, R. B., Soil Mechanics in Engineering Practice, 2nd ed., John Wiley & Sons, Inc., 1968, pp. 107, 32, 173-183, 217-225

4-3. Peck, R. B., Hanson, W. E. and Thornburn, T. H., Foundation Engineering, 2nd ed., John Wiley & Sons, Inc., 1974, p. 310

4-4. Deere, D. U. and Miller, R. P., "Engineering Classification and Index Properties of Intact Rock," Technical Report No. AFWL-TR-65-116, Air Force Weapons Laboratory, Kirkland AFB New Mexico, 1966, pp. 136-160

4-5. Dodds, D. J. and Schroeder, W. L., "Factors Bearing on the Interpretation of In Situ Testing Results," 2nd RETC, Vol. 1, pp. 397-414

4-6. Tarkoy, P. J., "Rock Index Properties to Predict Tunnel Boring Machine Penetration Rates," 2nd RETC, Vol. 1, p. 415

Section 4 (cont'd)

4-7. Gamble, J. C., "Durability-Plasticity Classification of Shales and Other Argillaceous Soils," Ph.D. Thesis, University of Illinois, 1971

4-8. Fenix & Scisson, Inc. and Arthur D. Little, "A Systems Study of Soft Ground Tunneling," Final Report for the Department of Transportation Report No. DOT-FR-9-0034, May 1970, pp. 11-12

4-9. Navdocks DM-7, Design Manual for Soil Mechanics, Foundations, and Earth Structures, prepared by the Department of the Navy, March 1971, pp. 7-3-8, 7-3-9, 7-3-14, 7-3-10

4-10. Lambe, T. W. and Whitman, R. B., Soil Mechanics, John Wiley & Sons, Inc., 1969, pp. 35, 452, 155, 36, 37

4-11. Bhore, J. (Personal Communication)

4-12. Coulson, J. H., "Shear Strength of Flat Surfaces in Rock," Stability of Rock Slopes, 13th Symposium on Rock Mechanics, ASCE, Illinois, 1971, pp. 77-105

4-13. Leps, T. M., "Review of Shearing Strength of Rockfill," ASCE JSMFD, Vol. 96, No. SM4, July 1970, pp. 1159-1170

4-14. Marachi, N. D. and others, "Evaluation of Properties of Rockfill Materials," ASCE JSMFD, Vol. 98, No. SM1, January 1972, pp. 95114

4-15. Dumbleton, M. J. and West, G., "Guidance on Planning, Directed and Reporting Site Investigations," Department of the Environment, TRRL Report LR 625, London, 1974

4-16. Wilson, S. D., "Suggested Method of Test for Moisture-Density Relations of Soils Using Harvard Compaction Apparatus," Special Procedures for Testing Soil and Rock for Engineering Purposes, ASTM STP-479, 1970, pp. 101-103

4-17. Haller, H. F., "Study of Interrelationship of In-Situ Rock Properties, Excavation Method, and Muck Properties," Final Report to Advanced Research Project Agency, NTIS No. AD-742 781, July 1973, 284 pp.

4-18. Woolf, D. D., The Identification of Rock Types, U. S. Department of Commerce, Bureau of Public Roads, November 1960 (available through United States Government Printing Office, Washington, D.C.)

4-19. Fumagalli, E., "Tests on Cohesionless Materials for Rockfill Dams," ASCE JSMFD, Vol. 95, No. SM1, January 1969, pp. 313-330

4-20. Marsal, R. J., "Large Scale Testing of Rockfill Materials," ASCE JSMFD, Vol. 93, SM2, March 1967, pp. 27-43

Section 4 (cont'd)

4-21. Peele, *Mining Engineering Handbook*, John Wiley & Sons, 3rd Edition, 1941

4-22. Lucke, W., Personal Communication

4-23. Mueser, Rutledge, Wentworth & Johnston, "Washington Metropolitan Area Rapid Transit, Authorized Basic System Connecticut Avenue Route, Subsurface Investigation," Vol. 1, NTIS PB-179653, December 1967

4-24. Mueser, Rutledge, Wentworth & Johnston, "Subsurface Investigation - Vol. 4, Washington Metropolitan Area Rapid Transit, Authorized Basic System Route and A Portion of the Pentagon Route," NTIS PB-185747, July 1969

4-25. Parsons-Brinkerhoff-Tudor-Bechtel, "Soil Investigation 5702: San Francisco-Market, San Francisco Bay Area Rapid Transit District," 28 August 1964

Section 5

5-1. Seelye, E. E., *Data Book for Civil Engineers*: Design, 3rd ed. John Wiley & Sons, Inc., 1960, pp. 9-12 to 9-13

5-2. Grant, R., "The Use of Compacted Fill Foundation Schemes for Multi-Story Buildings in the New England Area," JBSCES, ASCE, Vol. 61, No. 3, July 1974, pp. 124-131

5-3. The Commonwealth of Massachusetts, Department of Public Works, Standard Specification for Highways and Bridges, Boston, Massachusetts, 1973, pp. 351, 354, 369

5-4. Engineering Specification prepared by Haley & Aldrich, Inc., Cambridge, Massachusetts, Job File No. 3555

5-5. State Highway Department of Georgia - Standard Specifications for Roads and Bridges, Vol. I, January, 1965, pp. 810-811

5-6. New York State, Department of Public Works: Public Works Specifications, January, 1962, pp. 275, 374

5-7. Rutledge, P. C., "Utilization of Marginal Lands for Urban Development," ASCE JSMFD, Vol. 96, No. SM1, January 1970, pp. 1-22

5-8. Brunner, D. R. and Keller, D. J., "Sanitary Landfill Design and Operation," U. S. Environmental Protection Agency, 1972, p. 14

Section 5 (cont'd)

5-9. ASTM C330-69, "Standard Specification for Lightweight Aggregates for Structural Concrete," 1974 Annual Book of ASTM Standards, Part 14, pp. 229-232

5-10. ASTM C331-69, "Standard Specification for Lightweight Aggregates for Concrete Masonry Units," 1974 Annual Book of ASTM Standards, Part 14, pp. 233-235

5-11. ASTM C332-66, "Standard Specification for Lightweight Aggregate for Insulating Concrete," 1974 Annual Book of ASTM Standards, Part 14, pp. 236-239

5-12. Taylor, U. H., Concrete Technology and Practice, American Elsevier Publishing Co., 1965, p. 462

5-13. Washa, G. W., "Properties of Lightweight Aggregates and Lightweight Concretes," Journal American Concrete Institute, October, 1956, pp. 379, 380

5-14. ACI Manual of Concrete Inspection, reported by the American Concrete Institute, Publication SP-2, 5th ed., 1973

5-15. ASTM D692-71, "Standard Specification for Coarse Aggregate for Bituminous Paving Mixtures," 1974 Annual Book of ASTM Standards, Part 15, pp. 284-285

5-16. The Asphalt Handbook, prepared by The Asphalt Institute, Manual Series No. 4 (MS-4), 1965, p. 68

5-17. Anderson, A. G. and others, "Tentative Design Procedures for Riprap-Lined Channels," National Cooperative Highway Research Program Report 108, Highway Research Board, 1970

5-18. Taylor, A. P., "Trash Removal", Operating Problems in Sand and Gravel Production, National Sand and Gravel Association Circular No. 86, April, 1961

5-19. Peurifoy, R. L., Construction Planning Equipment and Methods, McGraw-Hill Book Company, 2nd ed., 1970, p. 273

5-20. Sowers and Sowers, Introductory Soil Mechanics and Foundations, The MacMillan Company, 3rd ed., 1970, pp. 206, 239

5-21. ASTM D1557-70, "Tests for Moisture-Density Relations of Soils, Using 10 Pound Rammer and 18 Inch Drop," 1974 Annual Book of ASTM Standards, Part 19, pp. 212-217

5-22. Hough, B. K., Basic Soil Engineering, The Ronald Press Company, 2nd ed., 1969, p. 512

5-23. D'Appolonia, D. J. and others, "Sand Compaction with Vibratory Rollers," ASCE JSMFD, Vol. 95, No. SM1, January 1969, pp. 263-284

5-24. Broms, B. and Forssblad, L., "Classification of Soils with Reference to Compaction, " Swedish Geotechnical Institute, 1968

5-25. Poulos, H. and Davis, E., Elastic Solutions for Soil and Rock Mechanics, John Wiley & Sons, Inc., 1974, 411 pp.

5-26. Johnson, S. J., "Precompression for Improving Foundation Soils," ASCE JSMFD, Vol. 96, No. SM1, January 1970, pp. 111-144

5-27. Leonard, G. A. (ed.), Foundation Engineering: Chapter 4 - Soil Stabilization by T. W. Lambe, McGraw-Hill Book Company, Inc., 1962, pp. 351-437

5-28. Woods, K. B. and others, Highway Engineering Handbook, McGraw-Hill Book Company, Inc., 1960, Chapter 21

5-29. Ritter, L. J. and Paquette, R. J., Highway Engineering, The Ronald Press Company, 3rd edition, 1967, Chapter 13

5-30. Ladd, C. C. and others, "Recent Soil-Lime Research at the Massachusetts Institute of Technology," paper presented to 39th Annual Meeting of the Highway Research Board, January 1960

5-31. Ingles and others, "Assessment of Mine Fill Properties, Warrego Mine, N. T.," Commonwealth Scientific and Industrial Research Organization Australia, Division of Applied Geomechanics Technical Report No. 19, 1973

5-32. Englehardt, K. and others, "Vibro-Replacement - A Method to Strengthen Cohesive Soils In Situ," ASCE National Structural Meeting, Cincinnati, Ohio, April 1974, Preprint No. 2281

5-33. Soil Compaction by Vibroflotation, A.I.A. File I-E, prepared by Vibroflotation Foundation Co., Pittsburgh, Pennsylvania

5-34. Webb, D. L. and Hall, R. V., "Effects of Vibroflotation on Clayey Sands," ASCE Speciality Conference on Placement and Improvement of Soils, MIT, 1968, pp. 393-405

5-35. Mitchell, J. K., "In-Place Treatment of Foundations Soils," ASCE JSMFD, Vol. 96, SM1, January, 1970, pp. 73-110

5-36. D'Appolonia, E. and others, "Sand Compaction by Vibroflotation," ASCE Transactions, Vol. 120, 1955, pp. 154-168

5-37. Tate, T. N., "World's Largest Drydock," CE, Vol. 31, No. 12, December, 1961

Section 5 (cont'd)

5-38. Bauman, V. and Bauer, G. E., "The Performance of Foundations on Various Soils Stabilized by Vibro-Compaction Method," Canadian Geotechnical Journal, Vol. 11, No. 4, November, 1974, pp. 509-530

5-39. Lyman, A. K., "Compaction of Cohesionless Foundation Soils by Explosives," ASCE Transactions, Vol. 107, 1942, pp. 1330-1348

5-40. Prugh, B. J., discussion of "In Place Treatment of Foundation Soils," by Mitchell, ASCE Specialty Conference on Placement and Improvement of Soil to Support Structures, MIT, 1970, p. 134

5-41. Pugh, B., "Densification of Soils by Explosive Vibrations," ASCE JCD, Vol. 89, No. CO1, March, 1963, pp. 79-100

5-42. Wild, P. A. and Haslam, E. F., "Towers and Foundations for Project EHV," ASCE JPD, Vol. 88, No. PO2, July 1962, pp. 69-111

5-43. Meyerhof, G. G., "The Design of Franki Piles with Special Reference to Groups in Sand," Proceedings, Symposium on Design of Pile Foundations, Stockholm, 1960, p. 105

5-44. Lehr, H., "Foundation Engineering Problems in Loess Soils," Proceedings 3rd Asian Regional Conference on Soil Mechanics and Foundation Engineering, Haifa, 1967, pp. 20-24

5-45. Abeley, Y. M. and Askalonov, V. V., "The Stabilization of Foundations for Structures on Loess Soils," Proceedings, 4th International Conference on Soil Mechanics and Foundation Engineering, London, Vol. 1, 1957, pp. 259-263

5-46. Lippold, F. H., "Cement and Clay Grouting of Foundations: Pressure Grouting with Packers," TASK Committee on Cement and Clay Grouting, ASCE JSMFD, Vol. 84, No. SM1, February 1958

5-47. Karol, R. H., Soils and Soil Engineering, Prentice Hall, 1960

5-48. Mayer, A., "Cement and Clay Grouting of Foundations: French Grouting Practice," Task Committee on Cement and Clay Groutings, ASCE JSMFD, Vol. 84, No. SM1, February 1955

5-49. Hughes, J. M. and Withers, N. J., "Reinforcing of Soft Cohesive Soils with Stone Columns," Ground Engineering, Vol. 7, No. 3, May 1974, pp. 42-49

5-50. __________"Vibroflotation Treats Nottingham Redevelopment Land," Ground Engineering, Vol. 8, No. 1, January 1975

5-51. Casagrande, L., "Electro-Osmotic Stabilization of Soils," JBSCE, Vol. 93, January 1952, pp. 51-83

Section 5 (cont'd)

5-52. Gray, D. H. and Mitchell, J. K., "Fundamental Aspects of Electro-Osmosis In Soils," ASCE JSMFD, Vol. 93, No. SM6, November 1967, pp. 209-236

5-53. Casagrande, L., "Review of Past and Current Work on Electro-Osmotic Stabilization of Soils," Harvard Soil Mechanics Series No. 45, December 1953

5-54. Bjerrum and others, "Application of Electro-Osmosis on a Foundation Problem in a Norwegian Quick Clay," Geotechnique, Vol. XVII, No. 3, September 1967, pp. 214-235

5-55. Barron, R. A., "Consolidation of Fine-Grained Soils by Drain Wells," ASCE Transactions, Vol. 113, 1948, pp. 718-754

5-56. Johnson, S. J., "Foundation Precompression with Vertical Sand Drains," ASCE JSMFD, Vol. 96, No. SM1, pp. 145-175

5-57. Healy, K. A. and Long, R. D., "Prefabricated Fin Underdrain Promises Faster Soil Drainage," CE, Vol. 44, No. 4, April 1974

5-58. Litvinov, I. M., "Stabilization of Settling and Weak Clayey Soils by Thermal Treatment," Highway Research Board, Special Report No. 60, 1960, pp. 94-112

Section 6

6-1. Walton, M. S. "Technological Innovation, The Problem of Risks and Incentives in Underground Construction," 2nd RETC, Vol. 1, p. 83

6-2. Garrison, W. L., "Social, Economic, and Planning Impacts of Rapid Excavation and Tunneling Technology," 2nd RETC, Vol. 1, pp. 313-324

6-3. Hammond, D. G. and Bertelsen, V. C., "An Owner's Viewpoint on Owner-Engineer-Contractor Relationships in Tunneling," 1st RETC, Vol. 1, pp. 801-813

6-4. Alldredge, W. S., "Washington Metropolitan Area Transit Authority's Experience with Contractual Relationships in Tunneling Contracts," 2nd RETC, Vol. 2, pp. 1137-1162

6-5. Pilcarsky, M., "Sixty Years of Rock Tunneling in Chicago," ASCE JCD, Vol. 97, No. CO2, November 1971

6-6. Gordon, G. P., "The Priceless Ingredients," 2nd RETC, Vol. 2, pp. 1445-1454

6-7. Sowers, G. F., "Changed Soil and Rock Conditions in Construction," ASCE JCD, Vol. 97, No. CO2, November 1971

Section 6 (cont'd)

6-8. Benson, R. P. and others, "The Effect of Foliation Shear Zones on Underground Construction in the Canadian Shield," 2nd RETC, Vol. 1, pp. 615-641

6-9. Corwin, T. J., "Tunnels -The Owners' Problems," 2nd RETC, Vol. 2, pp. 1455-1462

6-10. "Atlanta Starts $2.1-Billion Transit System," ENR, 27 February 1975

6-11. Lynch, F. L. and Knight, K. G., "A Common Sense Approach to Control of Construction Noises in Urban Areas," 2nd RETC, Vol. 1, pp. 483-494

6-12. Baldwin, J. R. and others, "Causes of Delay in the Construction Industry," ASCE JCD, Vol. 97, No. CO2, November 1971

6-13. Carleton, J. C., "An Environmentalist's Views on Underground Construction," 2nd RETC, Vol. 1. pp. 599-612

6-14. O'Neil, R. S., "Influence of Geographic, Demographic, Geologic, and Economic Factors in Planning Urban Transportation Systems," 2nd RETC, Vol. 1, pp. 351-356

6-15. Cooper, M. M. and Sigman, S., "Material Handling in Urban Areas," 2nd RETC, Vol. 1, pp. 427-444

Section 7

7-1. Rutledge, P. C., "Utilization of Marginal Lands for Urban Development," ASCE JSMFD, Vol. 96, No. SM1, pp. 1-22

7-2. Moore, W. W. and Chryssaforpoulos, N., "Sample Approaches to Optimum Use of Marginal Lands," ASCE JSMFD, Vol. 98, SM3, March 1972, pp. 243-263

7-3. Lee, D. B., "Analysis of BART Impacts on Bay Area Land Use" ASCE TEJ, Vol. 98, No. T3, May 1972, pp. 243-263

7-4. Parker, A. D., "Notes on Selection of Tunnel Excavation Systems," TT, Vol. 2, No. 2, March 1971

Section 8

8-1. Prince George's County Grading Ordinance (Article 22) and the Building & Grading Permits Guide (May 1974)

Section 10

10-1. Knoerle, Bender, Stone, & Assoc., Consulting Engineers for the City of Chicago Department of Development and Planning, 18 September 1973 "Lakefront Land Development Alternatives Report", 78 pp.

Section 10 (cont'd)

10-2. DeLeuw-Novick, Consulting Engineers, a letter report for the Chicago Urban Transportation District, 2 May 1974

10-3. The Flood Control Coordinating Committee, "Development of A Flood and Pollution Control Plan for the Chicagoland Area: Summary of Technical Reports," prepared by August, 1972

10-4. Letter of transmittal from Lewis W. Hill, City of Chicago Commissioner, to Marshall Suloway, Acting Commissioner, dated 6 June 1974. Subject: response to DeLeuw-Novick spoil disposal program for the Chicago Urban Transportation District

10-5. Urban Mass Transportation Administration, U. S. Department of Transportation, "Metropolitan Atlanta Rapid Transit System-Final Environmental Statement: Project GA-03-0008," 9 May 1973, NTIS No. EIS-GA-73-0799-F

10-6. Parsons-Brinckerhoff-Tudor-Bechtel, "Metropolitan Atlanta Rapid Transit Authority Bidders Information Pamphlet," October 1974

10-7. Parsons-Brinckerhoff-Tudor-Bechtel, "Metropolitan Atlanta Rapid Transit Authority Standard Specifications, Parts A & B," August 1974

10-8. Atlanta Airport Engineers, "Summary William B. Hartsfield Atlanta International Airport Layout Plan Report," August 1973

10-9. __________, "Atlanta Starts 2.1 Billion Transit System," ENR 27 February 1975

10-10. Urban Mass Transportation Administration, U. S. Department of Transportation, "Final Environmental Statement-Baltimore Region Rapid Transit System, Phase 1; Section A: Project MD-03-0004," September 1972

10-11. Miscellaneous fact sheets and pamphlets from the Baltimore Mass Transit Authority.

10-12. Robert B. Balter, Soil and Foundation Consultants, Inc., "Preliminary Subsurface Design Study-Phase 1," Northwest Line (Volume 1 and 2) and South Line (Volume 1 and 2), June 1974 (Northwest Line) and August 1974 (South Line)

10-13. Robert B. Balter, Soil and Foundation Consultants, Inc., "Bolton Hill Section, Geotechnical Data," (Volumes 1-4), May 1975

10-14. Robert B. Balter, Soil and Foundation Consultants, Inc., "Bolton Hill Station Inspection Shaft," Dec. 1975

10-15. Haley & Aldrich, Inc., "Status Report - Muck Utilization Study, MTA Tunnel Project, Baltimore, Maryland," 19 July 1976

Section 10 (cont'd)

10-16. Moshe Safde and Associates, "Coldspring - A Report to the City of Baltimore on Creation of a New Community in Northwest Baltimore," October 1972

10-17. Conrad Associates," Technical Report Engineering Study Coldspring Newtown," 1972

10-18. Robert B. Balter, Soil and Foundation Consultants, Inc., "Soil Profiles - Charles Center Station," 1976

Literature Search

1. Traylor, T. W., "The Romeo Tunnels - Detroit, Michigan," 1st RETC, Vol. 2, pp. 1113-1123

2. Geary, D. W., "Nast Tunnel Excavation History," 1st RETC, Vol. 2, pp. 1137-1147

3. Varello, J., "Difficult Excavation at Corley Porter," CE, Vol. 40, No. 6, June 1970

4. Beaulieu, A. C., "Tunneling Experiences, City of Edmonton, Alberta, Canada," 1st RETC, Vol. 2, pp. 933-963

5. Arthur, H. G., "Stillwater Tunnel Project," 1st RETC, Vol. 2, pp. 965-981

6. Jenkins, G. F. and Hobden, P. S., "Tunneling Toronto, Canada 1970," 1st RETC, Vol. 2, pp. 1017-1034

7. Irons, J. and Westfall, D., "Rock Tunnels Recently Completed in Chicago," 1st RETC, Vol. 2, pp. 1063-1076

8. Claassens, G. C., "Machine Tunnelling in Hard Rock," Proceedings South African Tunnelling Conference, Vol. 1, 1970, pp. 209-216

9. Stevens, V. I., "Mechanical Tunnel Boring," Proceedings South African Tunnelling Conference, Vol. 1, 1970, pp. 223-226

10. Pakes, G., "The Mersey Outfalls Interceptor, Sewer at Warrington, Lancs," TT, Vol. 3, No. 6, November 1971, pp. 415-417

11. Haries, D. A., "Mexico: Constructing the Deep Level Drainage System of Mexico City," TT, Vol. 3, No. 1, January 1971, pp. 35-43

12. Davie, J., "Tunnels in the Tongariro Power Development," TT, Vol. 3, No. 6, November 1971, pp. 420-424

Literature Search (cont'd)

13. Gilmour, L. W., "Tunnels for Tongariro Power Development," TT, Vol. 4, No. 6, November 1972, pp. 521-524

14. __________, "Sealing Rings for Elbe River Tunnel in Hamburg," TT

15. Richardson, "Constructing a Soft Ground Tunnel Under Boston Harbor," CE, Vol. 31, No. 1, January 1961, pp. 42-45

16. Lamba, S. S., "Beaus - Sutle; Link Project in India," TT, Vol. 3, No. 2, March 1971, pp. 87-93

17. Budders, B. L., "Brixton Extension of the Victoria Line," TT, Vol. 3, No. 4, July 1971, pp. 235-242

18. de Caminos, "Madrid Metro Current Works," TT, March 1972

19. Sacrison, "Flathead Railroad Tunnel," ASCE JCD, Vol. 97, CO1, March 1971

20. Maevis, "Planning Designing for 63rd Street East River Tunnel," ASCE Preprint No. 1229, July 1970

21. Ellinger, "The Viennese Subway System," Proceedings International Conference on Planning and Design of Tall Buildings, August 1972

22. Knight, "Subway Tunnel Construction in New York City," ASCE JCD, Vol. 90, No. CO2, September 1964, pp. 15-36

23. MacDonald, F., "The Thames Tunnel," Underground Services, Vol. 2, No. 2, 1974

24. Mayo, R. S., "Machine Tunneling in Chicago Clays," CE, Vol. 34, No. 2, February 1964, p. 60

25. Low, J., "Soil Freezing to Reconstruct a Railway Tunnel," ASCE JCD, Vol. 86, No. CO4, November 1960

26. Peraino, J., "Chesapeake Bay Bridge - Tunnel Project, Two Tunnels and Four Islands," CE, Vol. 33, No. 12, December 1963

27. Stewart, W. K. and others, "Tunnel Under New York Harbor," CE, Vol. 33, No. 4, April 1963, p. 52

28. Lanning, C., "Orville Dam Diversion Tunnels," ASCE JPD, Vol. 93, No. PO2, October 1967, p. 51

29. Underwood, L. B., "Machine Tunneling in Missouri River Dams," ASCE JCD, Vol. 91, No. CO2, May 1965

30. Blaschke, T., "Underground NORAS Command Center at Colorado Springs," CE, Vol. 34, No. 5, May 1964

Literature Search (cont'd)

31. Elchstaedt, H. M., "California - Highway Tube Under San Francisco Bay," CE, Vol. 32, No. 3, March 1962

32. Murphy, G. J., "Foundation Problems on the Second Elizabeth River Tunnel," CE, Vol. 33, No. 7, July 1963

33. Kauno, K., "Limfjord Tunnel: Precast Sections in Underwater Trench," CE, Vol. 39, No. 7, July 1969

34. Bird, J. W., "Storm Sewer Tunnel in St. Paul," CE, Vol. 33, No. 8, September 1963

35. __________, "Baltimore Harbor Tunnel," CE, Vol. 25, No. 10, October 1955

36. __________, "Bankhead Tunnel, Mobile, Alabama," CE, Vol 25, No. 10, October 1955, p. 82

37. __________, "Berkeley Hills Tunnel Completed," RS, May 1967

38. __________, "Bloor St. Subway, Toronto," ENR, March 1960, pp. 37-39

39. __________, "Bowery Bay Disposal Plant Sewer Tunnel, New York," ENR, November 1955, pp. 34-38

40. __________, "First Vehicle Tunnel Crosses the Type," ENR, October 1967

41. __________, "Lincoln Tunnel, Third Tube, New York," ENR, February 1956

42. __________, "Mass River Tunnel, Rotterdam," CE, Vol. 25, No. 10, October 1955, p. 82

43. __________, "Milwaukee Concrete Sewer Tunnel," ENR, July 1969

44. __________, "Montreal Metro," ENR, September 1964

45. __________, "New York Subway Cut and Cover," ENR, March 1964

46. __________, "Norfolk - Portsmouth Tunnel, Virginia," ENR, January 1962, pp. 94-95

47. __________, "Velsen Tunnel, Holland," ENR, March 1957, pp. 54-56

48. Young, E. M., Jr., "Tunnels Claw, Shove Through Clay Under Boston Harbor," ENR, September 1960

APPENDIX A

RESPONDENTS TO SURVEY AND SURVEY FORM

A two page survey, attached at the end of this appendix, was distributed to owners, contractors, engineers, and planning agencies. The 75 responses were received from nineteen organizations as follows:

	No. Organizations		No. Responses	
	U.S.	Foreign	U.S.	Foreign
Owners	0	1	0	1
Contractors	7	1	25	27
Engineers	6	3	13	7
Planning Agencies	1	0	2	0

The following lists all those organizations who reported:

I. United States

Bauer Engineering, Inc.
20 N. Wacker Drive
Chicago, Illinois 60606

Bechtel Corporation
Box 6189
Ben Franklin Street
Washington DC 20044

Expressway Constructors
P.O. Box 2748
Arlington, Virginia 22202

Granite Construction Company
P.O. Box 5038
Austin, Texas 78763

Greenfield Construction Company, Inc.
Box 2185
13040 Merriman Road
Livonia, Michigan 48151

S. A. Healy Company
Box 11
McCook, Illinois 60525

Mason & Hanger - Silas Mason Company, Inc.
437 Madison Avenue
New York, New York 10022

A. A. Mathews, Inc.
41 W. Santa Clara Street
Arcadia, California 91006
also
230 Park Avenue
New York, New York 10017

Metropolitan Sanitary District of Greater Chicago
101 Ontario
Chicago, Illinois 60611

Moramer & Hartnell, Inc.
4716 S Street
Kenilworth, Washington DC 20027

Nello L. Teer Company
1220 N. Herndon Street
Arlington, Virginia 22201

Parsons, Brinckerhoff - Tudor, Bechtel
425 Market Street
San Francisco, California
also
50 Beale Street
San Francisco, California
also
663 South Van West
San Francisco, California

S & M Constructors, Inc.
29125 Hall Street
Solon, Ohio 44139

Traylor Bros., Inc.
Box 5165
Evansville, Indiana 47715

II. Foreign

E. Roy Anderson
29 Jen AI Road
Sec., 4 Apt. 5A
Taipei, Taiwan

Consultores Gerais Ltda.
Caixa Pastal 30125
Sao Paulo, Brazil

Fried. Krupp Gmdlt, Krupp Universalbac
43 Essen
Buddestrausse 4, Germany

Obayashi - Gumi, Ltd.
3, 2 -Chome, Kanda Tsukasa -Cho
Chiyoda -Ku,
Tokyo, Japan

Toronto Transit Commission
1900 Yonge Street
Toronto, Ontario M4S 1Z2
Canada

SURVEY FORM

Circle description which best fits.

1. Name of Excavation ______________________________ Length________
   Location ______________________________________ Size ________
2a. Type of Excavation - Cut & Cover Tunnel Other ________
2b. Use of Excavation - Subway, Railroad, Water, Sewer, Utility, Vehicular, Other ______________________________
3. Type and Condition of Ground - Hard Rock, Soft Rock, Sand, Clay, Silt, Wet, Dry, Moist, Other ______________________________
4. Was a soil or rock exploratory program conducted? Yes No
   If answer is Yes, were the number of borings adequate to define all conditions encountered? Yes No
   If No, explain ______________________________
   ____
5. Volume of Excavated Material Rock ______m^3 Sand ________m^3
   Clay ______m^3 Silt _______m^3 Other __________m^3 Other _____m^3
   Was muck modified/treated in any way before/after use? Yes No
   a) By whom? ______________________________
   b) Describe______________________________
6. How was excavated material used? ______________________________
   ____
   ____
7. Was excavated material suitable for the construction of future structures thereon after placement? Yes No
   If No, describe ______________________________
   ____
8. Was Contractor directed to dispose of the muck in a specific location? Yes No
   If Yes, describe method of instruction (i.e. specifications, etc.)
   ____
   ____
   If No, describe Contractor's procedures for finding locations to dispose of muck______________________________
   ____

8. (cont).

Was muck sold? Yes No

By Whom? ____________________

To Whom? ____________________

9. Was the utilization of the excavated material (muck) beneficial to the public interest? Yes No

Explain: ____________________

____

____

10. Additional comments (use additional sheets if required)

____

____

____

____

____

By: Name ____________________

Company: ____________________

Address: ____________________

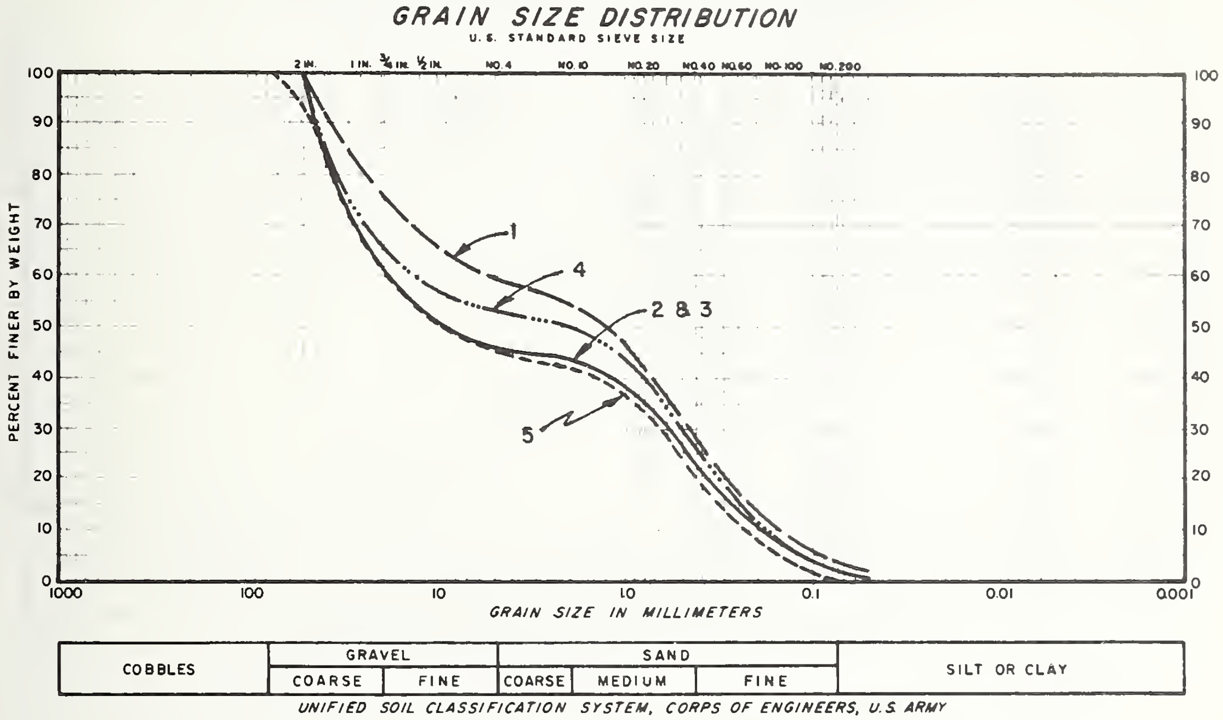
____

____

Telephone No. ____________________

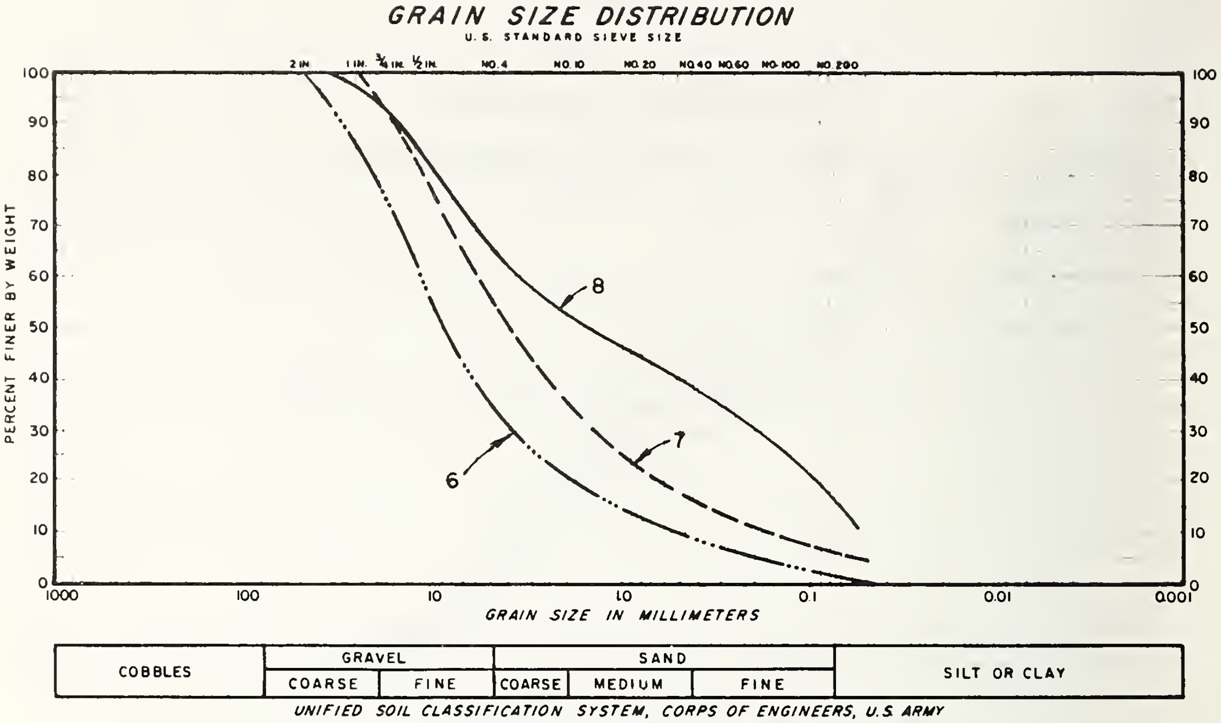
APPENDIX B

TYPICAL GRADATION CURVES FOR ROCK MUCK



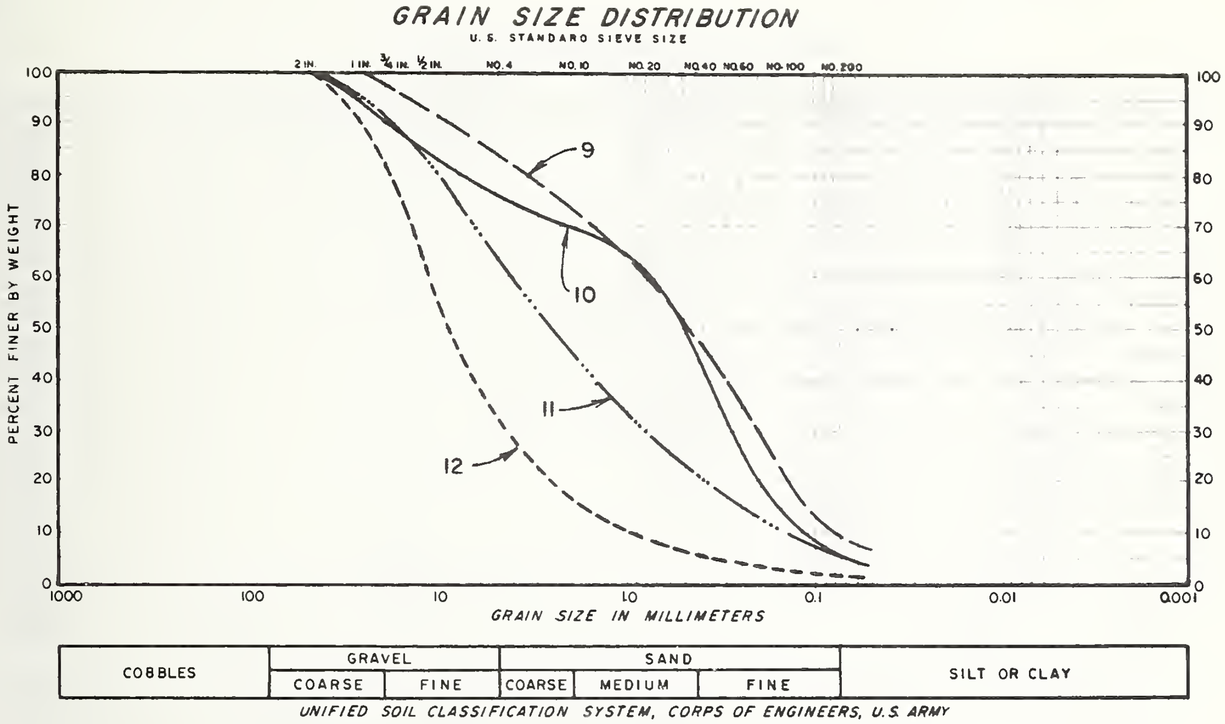
Sample No.	Description	Coefficient of Uniformity, C_U	Coefficient of Curvature, C_C
1	gravelly coarse to fine SAND	40	0.3
2 & 3	gravelly coarse to fine SAND	95	0.1
4	gravelly coarse to fine SAND	68	0.1
5	gravelly coarse to fine SAND	83	0.1

FIGURE B-1. GRADATION CURVES FOR TBM MUCK, SAMPLES 1 THROUGH 5 [3-16]



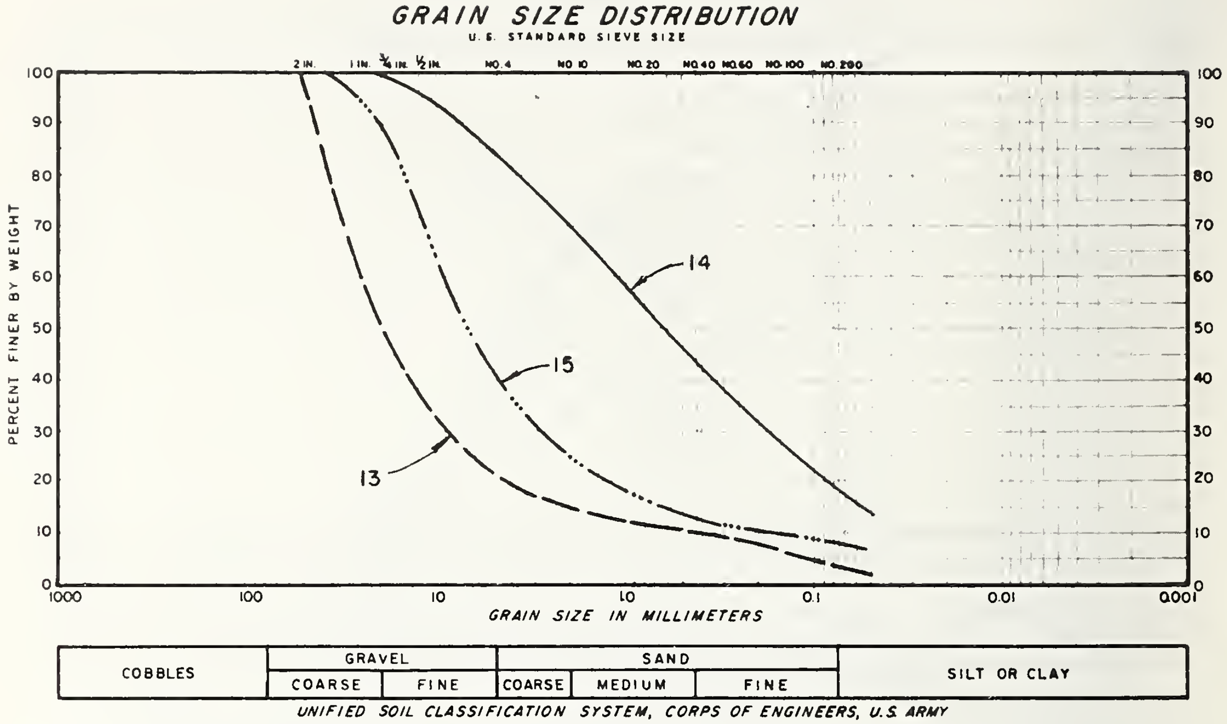
Sample No.	Description	Coefficient of Uniformity, C_U	Coefficient of Curvature, C_C
6	sandy coarse to fine GRAVEL	24	2.7
7	gravelly coarse to fine SAND, trace silt	38	2.0
8	gravelly coarse to fine SAND, trace silt	66	0.2

FIGURE B-2. GRADATION CURVES FOR TBM MUCK, SAMPLES 6 THROUGH 8 [3-16]



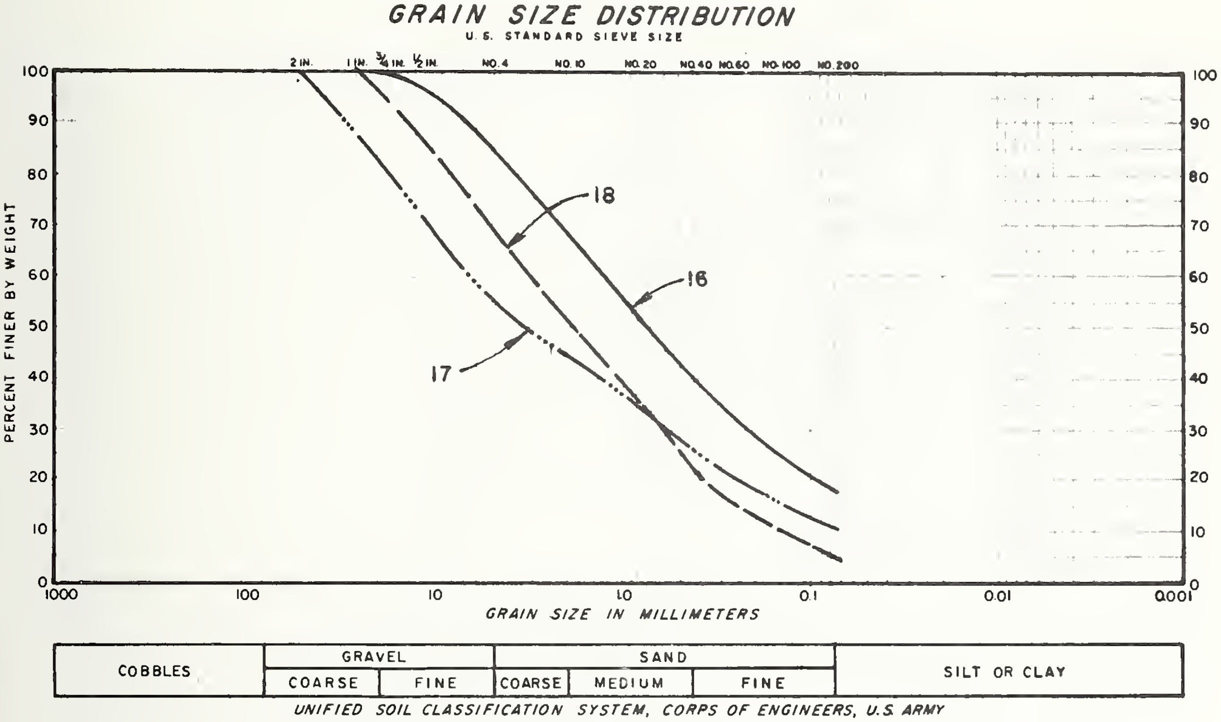
Sample No.	Description	Coefficient of Uniformity, C_U	Coefficient of Curvature, C_C
9	coarse to fine SAND, little gravel	10	0.6
10	coarse to fine SAND, little gravel	6	0.8
11	gravelly coarse to fine SAND	29	1.1
12	sandy coarse to fine GRAVEL	13	1.4

FIGURE B-3. GRADATION CURVES FOR TBM MUCK, SAMPLES 9 THROUGH 12 [3-16]



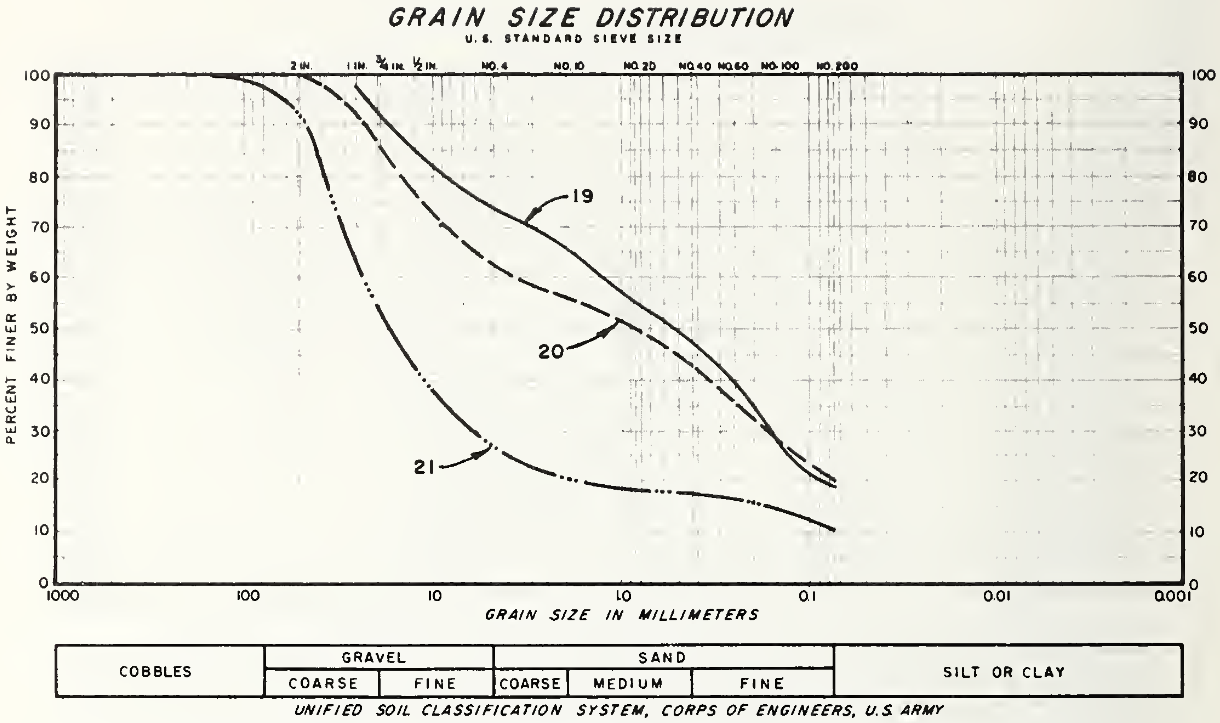
Sample No.	Description	Coefficient of Uniformity, C_U	Coefficient of Curvature, C_C
13	coarse to fine GRAVEL, little sand	63	7.9
14	coarse to fine SAND, little gravel, little silt	28	0.6
15	sandy coarse to fine GRAVEL, trace silt	56	5.8

FIGURE B-4. GRADATION CURVES FOR TBM MUCK, SAMPLES 13 THROUGH 15 [3-16]



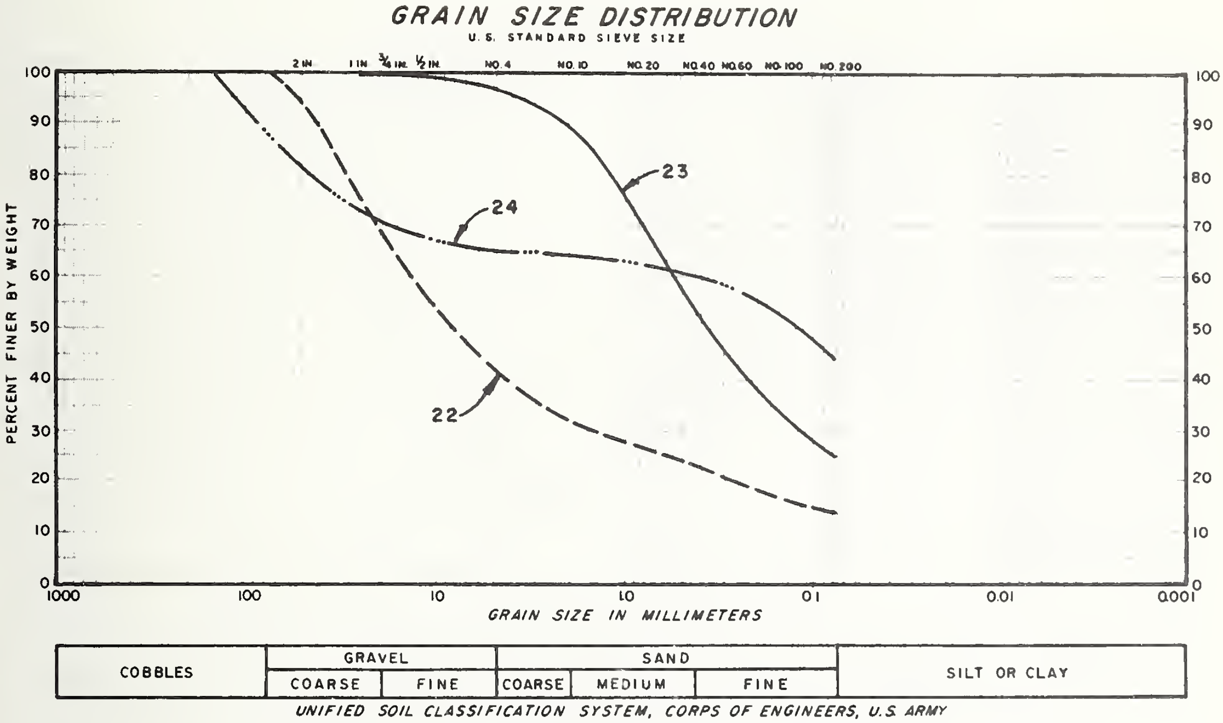
Sample No.	Description	Coefficient of Uniformity, C_U	Coefficient of Curvature, C_C
16	coarse to fine SAND, little silt, little gravel	43	1.1
17	sandy coarse to fine GRAVEL, little silt	97	0.8
18	gravelly coarse to fine SAND	22	0.8

FIGURE B-5. GRADATION CURVES FOR TBM MUCK, SAMPLES 16 THROUGH 18 [3-15]



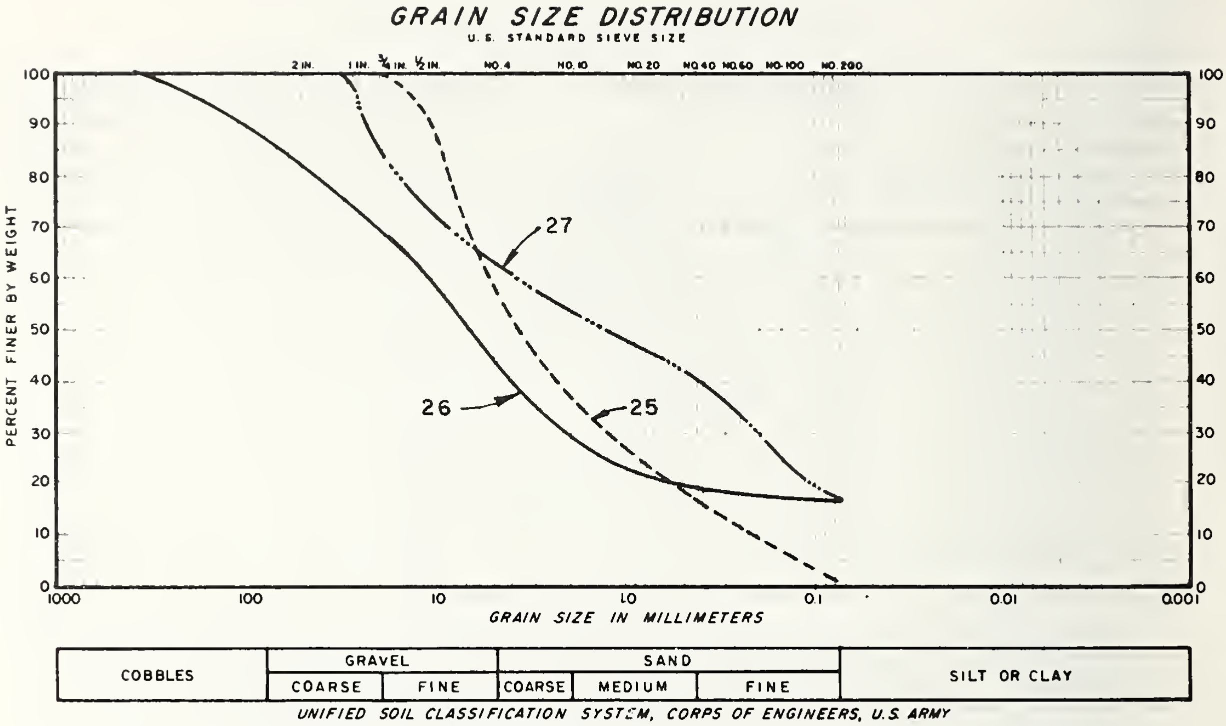
Sample No.	Description	Coefficient of Uniformity, C_U	Coefficient of Curvature, C_C
19	gravelly coarse to fine SAND, little silt	40	0.6
20	gravelly coarse to fine SAND, little silt	120	0.2
21	coarse to fine GRAVEL, little sand, trace silt	329	24.7

FIGURE B-6. GRADATION CURVES FOR TBM MUCK, SAMPLES 19 THROUGH 21 [3-15]



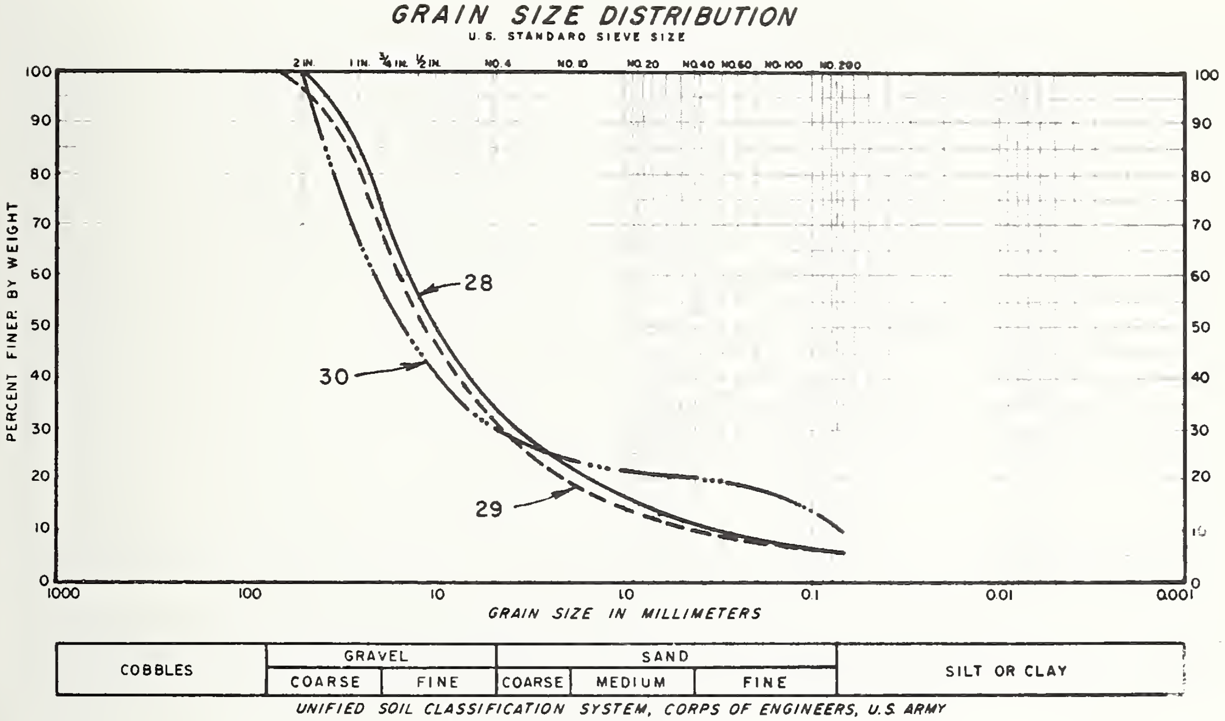
Sample No.	Description	Coefficient of Uniformity, C_U	Coefficient of Curvature, C_C
22	sandy coarse to fine GRAVEL, little silt	325	3.3
23	silty coarse to fine SAND	18	0.8
24	gravelly SILT, little sand, trace cobbles	--	--

FIGURE B-7. GRADATION CURVES FOR TBM MUCK, SAMPLES 22 THROUGH 24 [3-15]



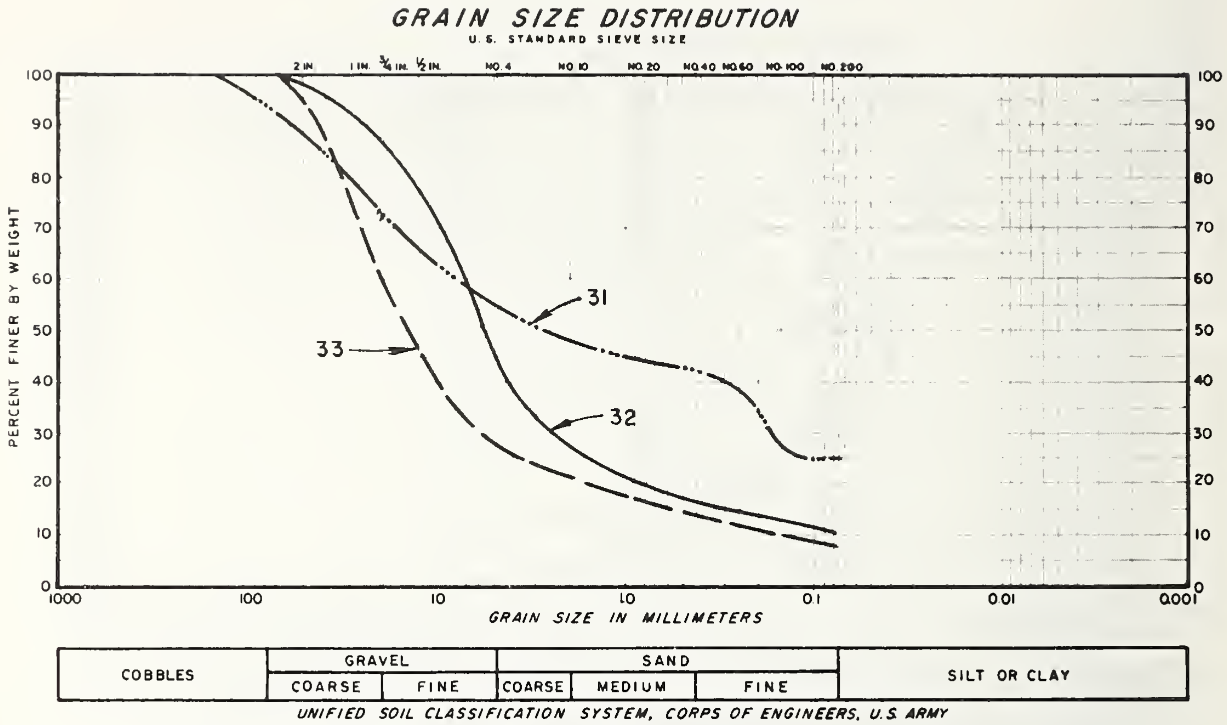
Sample No.	Description	Coefficient of Uniformity, C_U	Coefficient of Curvature, C_C
25	gravelly coarse to fine SAND	26	1.5
26	sandy coarse to fine GRAVEL, trace cobbles	--	--
27	gravelly coarse to fine SAND, little silt	133	0.3

FIGURE B-8. GRADATION CURVES FOR TBM MUCK, SAMPLES 25 THROUGH 27 [3-15]



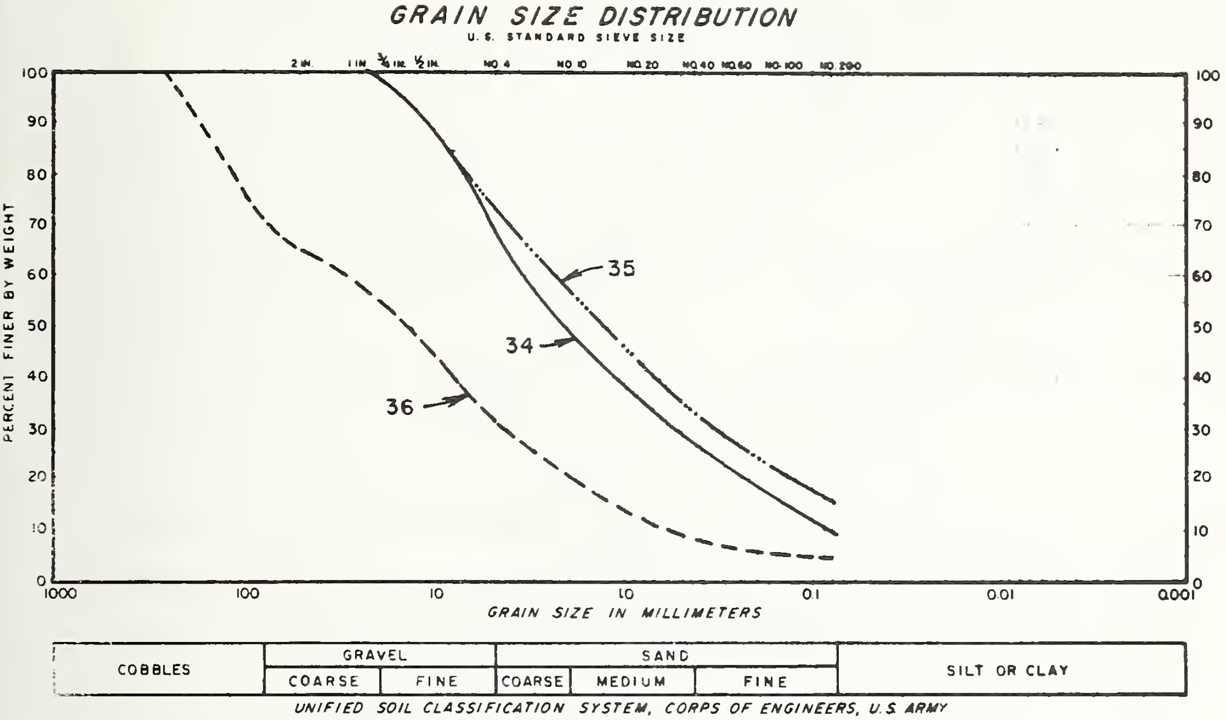
Sample No.	Description	Coefficient of Uniformity, C_U	Coefficient of Curvature, C_C
28	sandy coarse to fine GRAVEL, trace silt	47	3.6
29	sandy coarse to fine GRAVEL, trace silt	38	4.0
30	sandy coarse to fine GRAVEL, trace silt	300	16.3

FIGURE B-9. GRADATION CURVES FOR TBM MUCK, SAMPLES 28 THROUGH 30 [3-15]



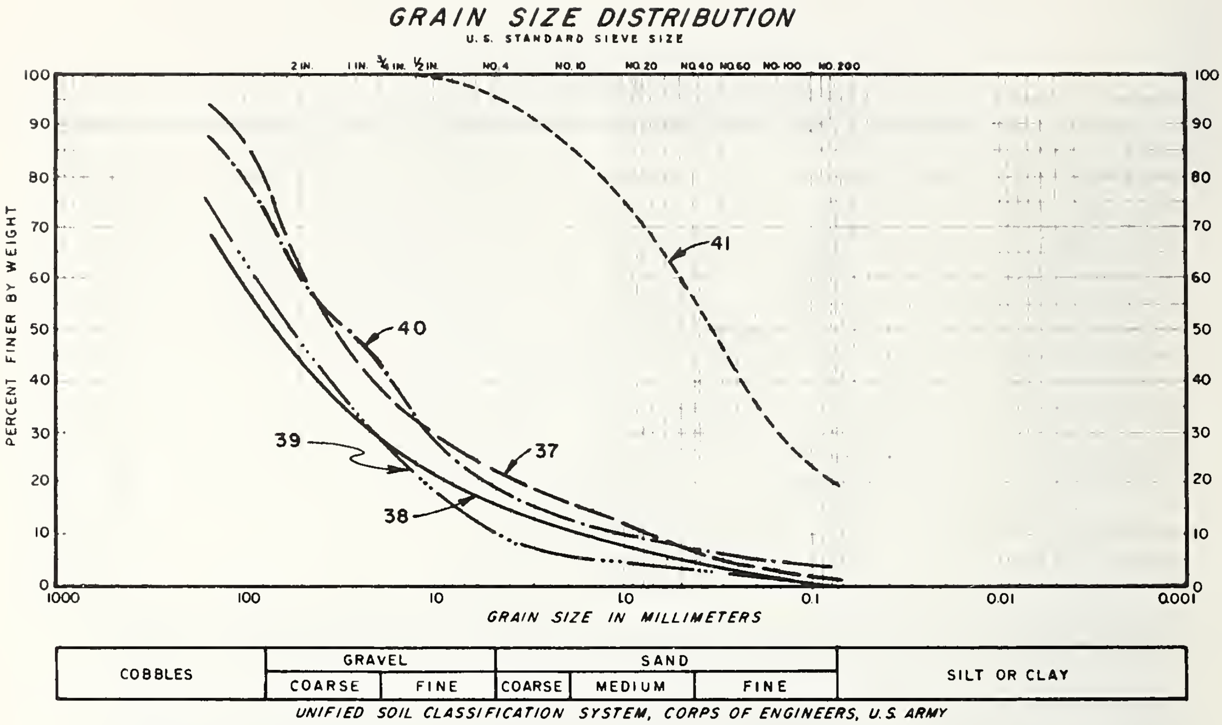
Sample No.	Description	Coefficient of Uniformity, C_U	Coefficient of Curvature, C_C
31	sandy coarse to fine GRAVEL, some silt, trace cobbles	--	--
32	sandy coarse to fine GRAVEL, little silt	95	11.1
33	coarse to fine GRAVEL, little sand, trace silt	133	12.0

FIGURE B-10. GRADATION CURVES FOR TBM MUCK, SAMPLES 31 THROUGH 33 [3-15]



Sample No.	Description	Coefficient of Uniformity, C_U	Coefficient of Curvature, C_C
34	gravelly coarse to fine SAND, trace silt	43	1.1
35	gravelly coarse to fine SAND, little silt	52	1.0
36	sandy coarse to fine GRAVEL	50	1.0

FIGURE B-11. GRADATION CURVES FOR TBM MUCK, SAMPLES 34 THROUGH 36 [3-15]



Sample No.	Description	Coefficient of Uniformity, C_U	Coefficient of Curvature, C_C
37	coarse to fine GRAVEL with cobbles	70	2.9
38	coarse to fine GRAVEL with cobbles	58	2.6
39	coarse to fine GRAVEL with cobbles	18	0.9
40	coarse to fine GRAVEL with cobbles	50	2.4
41	coarse to fine SAND, little silt	15	2.4

FIGURE B-12. GRADATION CURVES FOR DRILL AND BLAST MUCK, SAMPLES 37 THROUGH 41 [3-15]

APPENDIX C

FUNCTIONAL STEPS FOR PROGRAM IMPLEMENTATION [10-1]

SOURCE: KBS; p. 67

1. Planning Studies, Reviews and Recommendations by the Chicago Department of Development and Planning.

2. Decision to Implement Program by Mayor.

3. Assignment of Program to Chicago Department of Public Works for Implementation.

4. Establish Organization for Program Administration, Staff and Fund.

   Some functional responsibilities are:

   (a) Research and Data Collection for Project.

      1) Evaluation of past and current research.

      2) Initiate and control new research and data collection.

      3) Liaison and coordinate with other agency data collection and instrumentation.

   (b) Engineering

      1) Studies, criteria, stage sequencing, surveys, investigations, etc.

      2) Design and Specifications, utility arrangements, etc.

      3) Contract Administration, technical inspection, materials control, etc.

   (c) Interagency Liaison and Coordination

      1) Interagency Agreements.

      2) Implementation of Policy Guidance.

      3) Maintain Channels of direction and information.

      4) Planning and Regulatory agency liaison.

      5) Liaison with all affected public agencies.

   (d) Financing and Cash Flow.

      1) Grant Applications.

      2) Requests for Appropriations.

3) Cash Flow and Bookkeeping.

4) Participating Agency Accounting.

(e) Information and Public Contact.

1) Public information and media.

2) Complaints and requests.

3) Public Hearings assistance.

4) Citizen Group Contact.

(f) Legal Liaison.

1) Determine needed and desirable legislation for all levels of Government.

2) Assist and provide information for preparation of Legislation.

3) Determine needs and assist in necessary acquisitions.

4) Provide information and assistance related to legal matters.

5) Legal aspects of interagency agreements.

5. Prepare Engineering Report for first stages of the project. Prepare Environmental Impact Statement for first stages of the project.

The preparation of these documents requires close coordination with participatory, policy and regulatory agencies and should utilize input from agencies which can provide advisory services.

The purpose of these documents is to provide a framework for design and to reduce the number of hearings and the time required for reviews of individual elements of the project.

Because of the need to coordinate with early construction schedules of portions of the Tunnel and Reservoir project, it will not be practical to delay initial critical element design until these documents are available. A certain risk that early designs may not be optimum in terms of the total project should be off-set by the sure value of being able to use the available spoil for landfill.

Determine Financing and Scheduling.

Tentative scheduling and financing developed in the Enginneering Report should be refined as detailed interagency agreements are developed.

6. Investigate Possible Participatory Agencies and Possible Funding Agencies and negotiate interagency agreements among the primary Agencies involved.

7. Establish Policy Guidance and Control Organization and Arrangements.

8. Formulate Design Criteria, standard specifications and set up procedures for initial contract administration and cash flow.

9. Prepare Preliminary designs for critical elements of first stage construction. This work includes field control surveys, lake bottom mapping, and necessary subsurface investigations. This step is critical with respect to timing as field work is constrained by weather and season.

10. Acquire needed riparian rights for the critical portions of the project. This work should begin as early in the project as possible and if pursued diligently may not be a critical consideration in scheduling.

11. Submit preliminary plans for first stage critical portions of the project and overall early stage Engineering Report, Environmental Studies and Impact Statements to regulatory agencies for review. Assist in publicity and public hearings. Obtain all necessary permits and approvals.

If both preliminary detail plans for critical portions of the project and reports for total early project stages can be coordinated so that reviews and hearings for both can be made at the same time, it should be possible to reduce the time required for reviews.

Normal reviews for public works projects vary in time from a few months to sometimes a year or two. It will be necessary to obtain commitments from reviewing agencies to set up special review channels and to assign priority to this project in order to shorten the time required for this step of the program.

(a) Regulatory Agency approvals.

1) All Federal approval requests are submitted to the U.S. Army Corps of Engineers who deal with the appropriate Federal Agencies and who will schedule and hold necessary public hearings.

2) All State of Illinois approval requests are submitted to the Department of Transportation who deal with the appropriate State Agencies.

3) Approval requests to Independent Bodies are handled individually.

4) Approval requests to City of Chicago Agencies would be handled by normal channels through the Department of Public Works.

(b) Policy Approvals should be channeled through a policy guidance control organization set up for that purpose.

(c) Participatory Agency approvals should be handled through normal coordination channels.

12. Begin field work and preliminary design work for second stage portions of the project. Prepare environmental statements.

This work should be scheduled to permit field work to be done without winter interruption.

13. Complete final design of critical contracts. Detail design work normally would continue during the period of regulatory agency review. A certain period of time after permits are received is necessary to put plans and contract documents in final form.

14. Approve, advertise and let critical contracts. This operation is standardized by each public agency. It is prudent to allow about 90 days for these contractual operations.

Contracts should be let as early in the year as possible to obtain better competitive bidding and to take full advantage of the construction season.

15. Begin construction of critical contracts.

16. Reviews and issue permits for the second stage design contracts. Public hearings may or may not be required.

17. Complete design of second stage contracts.

18. Approve, advertise and let second stage contracts for spring construction.

19. Repeat appropriate steps for future portions of the project.

APPENDIX D

REPORT OF INVENTIONS

The findings of this study, as reported herein, are primarily planning concepts and recommendations to be applied for utilization of excavated tunnel materials in tunnel construction. Development of these recommendations did not require the manufacture or preparation of patentable inventions. There were no patentable inventions or discoveries resulting from this work.

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